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NAVY DEPARTMENT

BUREAU OF ENGINEERING

Fifth Partial Report

on

Light Armor.

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The Effect of Yaw upon Penetration; the Effect upon Bullets of Penetrating very Thin Duralumin Sheets; and the Use of Shielding Structures in the Form of Gratings.

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ABSTRACT

Three investigations directly related to light armor for aircraft are described in this report: the effect of yaw upon penetration, the effect upon bullets of penetrating very thin Duralumin sheets, and the use of shielding structures in the form of gratings. Data illustrating these topics are still in the process of collection. Methods of these investigations are, however, described and preliminary results of interest are shown.

An effect of yaw upon penetration of about 1.4 per cent limit velocity increase per degree yaw was found for samples of 17 ST Duralumin, STS armor plate and hard homogeneous armor. The largest yaw effect was measured using a plate of STS armor hardened to Brinell 370. The smallest measured yaw effect was obtained on a sample of 1/4" face-hardened armor. It is shown that apparent differences in plate quality or bullet quality of 50 feet per second in plate testing may be due to several degrees of yaw of the bullets at impact.

If armor is spaced back inside the fuselage of an aircraft, bullets may tumble before striking the armor due to penetrating a Duralumin sheet at large obliquity. The effect of a shielding Duralumin sheet at 60 degrees obliquity and 23 inches separation on the limit of a typical bullet-proof plate at normal incidence is shown to be more than 200 feet per second. There is a gain in weight efficiency even when the resolved weight of the Duralumin is included with that of the armor plate.

The efficiency of a light grating used as the first plate of a divided armor structure depends considerably upon design. Certain design improvements have been ascertained. On account of the very large effectiveness of solid shielding plates, it is still uncertain whether gratings or solid plates are better as first members of a divided armor structure.

INTRODUCTION

1. Authorization. This problem was authorized by reference (a) and additional references pertinent to this problem are listed as (b) through (g).

Reference: (a) BuOrd.ltr. S13-1 (4/173) (Q8) of 13 December 1934.
(b) NRL Report No. O-1438.
(c) NRL Report No. O-1439.
(d) NRL Report No. O-1440.
(e) Aberdeen Proving Grounds Report No. 42, of 11 November 1936.
(f) BuOrd.ltr. S13-1 (4) (K13, Ma12), Light Armor for Airplanes, of 28 April 1938.
(g) NRL ltr. C-S13 of 15 May 1939.

2. Preceding Naval Research Laboratory reports, references (b), (c), and (d), have shown the general penetration characteristics of small caliber A.P. bullets as affected by their jackets, the possible usefulness of light alloys of the Duralumin and Dow metal type for armor, and the increased effectiveness of multiple plate structures when the plates are separated. These features of preceding light armor studies suggested it would be profitable to examine the effect upon bullets penetrating the Duralumin material used for covering aircraft fuselages. The resistance to penetration of light alloys plus tumbling effects upon bullets passing through a grating, suggested a divided armor structure might be more efficient on a weight basis when the first plate was a light grating of Duralumin. The stopping power of material when struck by projectiles with various amounts of yaw at impact is involved in both of these topics for investigation.

3. This report discusses three factors of importance with respect to the design of light armor structures: (a) the effect of yaw upon penetration; (b) the effect upon bullets of penetrating very thin Duralumin sheets; (c) the use of shielding structures in the form of gratings or light plates.

4. Other factors to be considered when estimating necessary weights of armor for making, say, armored seats of available material, are (a) and (b) of paragraph 3, as was suggested in reference (f).

5. In order to measure the effect of yaw upon penetration, Aberdeen Proving Ground, reference (e), fired caliber 50 A.P. bullets into 3-inch STS armor plates and measured depth of penetration as well as yaw and velocity. In addition a 1/4" face-hardened plate was subjected to impacts by caliber 30 A.P. bullets with measurement of yaw and velocity. The effect of each impact against the face-hardened armor plate was recorded as complete or partial, presumably by the Aberdeen Proving Ground's "light shows through" criterion for complete penetration. The bullets were fired at 100 yards through Aberdeen chronograph screens. Yaw cards were placed 12 inches in

front of test plates and yaw at impact was deduced upon the assumption of negligible rotation. The bullets were sometimes nicked and the barrels marred to obtain large amounts of yaw.

6. The results of the Aberdeen Proving Ground's tests were studied at the Naval Research Laboratory. The results obtained by firing into 3" thick plates cannot be interpreted in terms of penetration of smaller thicknesses. The measurements upon face-hardened armor indicate with reasonable accuracy about 0.7 per cent increase in limit velocity per degree yaw. The result was obtained on only one thickness of one material and was based upon a different criterion of penetration than is commonly used at the Naval Research Laboratory. No measurements are known of the effect of yaw upon penetration for small caliber A.P. bullets other than those mentioned above with the exception of the experiments conducted during the year 1938-1939 at the Naval Research Laboratory.

7. Caliber 30 A.P. bullets were fired at short range and normal incidence against plates of several different steels and against plates of Duralumin. A number of impacts were made at various amounts of yaw. By means of a velocity-yaw chart on which partial and complete penetrations were distinguished, it was possible to estimate the average effect over the interval from 0° to 15°. For other angles than normal obliquity, the effect is expected to depend upon orientation as well as magnitude of yaw. The measurements made, however, give a satisfactory, even though rough, estimate of yaw effects expected at small obliquities.

8. In order to determine the effect of passage of bullets through thin Dural such as is often used for covering aircraft fuselages, firings were conducted against 0.05" Dural sheets set at various angles of obliquity. A special limit determination was made upon a piece of .26" hard bullet-proof armor at normal incidence shielded by a sheet of 0.05" Dural at 60° obliquity.

9. A number of trials were made of gratings. In some cases the result using a grating was compared directly with the result when the grating was replaced by an equivalent weight flat plate of the same material. There are indications that gratings can be designed which will tumble bullets more efficiently than do equivalent weight flat plates. The results are still considered to be indefinite. Further experiments with Dural gratings, with STS gratings and thin plates, and with wire screens, are planned.

METHODS

10. Model 1922, caliber 30 A.P. bullets were fired at short range from a Mann barrel. Velocities at impact were estimated from Aberdeen chronograph records taken with screens 2 feet and 18 feet in front of the test plates. The range used was 42 feet. At this distance no special devices, such as nicking bullets, were needed to obtain amounts of yaw from 0° to 10° at impact. To get larger

amounts of yaw a piece of fabric board was sometimes placed at an angle with the trajectory between the chronograph screens.

11. Sheets of impregnated bakelite 1/32" thick and, at velocities above 1500 feet per second, 1/64" sheets of the same material were used as yaw cards. Cards of this material were placed about two inches from the front face of the test plate. From the clearly punched outlines obtained, yaw was measured with an accuracy of $\pm$ 1/2°. The yaw card records were compared directly with the shadow upon a translucent screen of a bullet mounted upon a rod capable of rotation. The angle of the axis of symmetry of the bullet with respect to the beam of light when the bullet was turned so as to just fill the yaw card record was read on a protractor scale graduated in 1/2 degrees.

12. Test plates of several thicknesses each of hard homogeneous armor, STS armor, mild steel, and 17 ST Duralumin were subjected to impacts by caliber 30 A.P. bullets at normal incidence. Each test plate was subjected to impacts at normal incidence until near limit velocity penetrations had been obtained for a number of values of yaw through the desired interval.

13. Sheets of 0.05" 24 ST Duralumin were perforated with caliber 30 A.P. bullets at 100 yards using obliquities of 45°, 60°, and 75°. Yaw of the bullets at 20 inches behind the Duralumin was measured. Some preliminary testing of this type was performed with bullets having less than 3 degrees yaw at impact. Although the measured amounts of yaw 20 inches behind the Duralumin did not correlate closely either with the yaw or with the obliquity at impact, a rough estimate of the average turning effect of such impacts was obtained. Testing a typical bullet-proof plate both with and without a shielding plate of thin Duralumin furnished a means of directly determining in a specific instance the increase of protection due to the turning effect mentioned above.

14. Of the Duralumin gratings tested, only one was tested as a means of itself of stopping projectiles. Other gratings tried were generally mounted at 30° obliquity with a 1/4" STS armor plate 6 to 9 inches behind. Efficiency of the grating was judged by the penetrating effect of the projectiles as they struck the STS armor plate.

DATA OBTAINED

15. Measurements of yaw were taken with two 1/32" bakelite yaw cards placed 2 inches apart. The difference in the yaw indication on the two cards varied from 0° to 1°. Therefore the change of yaw by nutation and by turning of the bullet during passage through a yaw card was 1° or less in 2 inches. In the actual firing for the effect of yaw upon penetration only one yaw card was used. This card was placed about 2" in front of the test plate. Since the yaw could be read from the card with an accuracy of 1/2° and a maximum change of one degree of yaw occurred between the card and the plate, the

measurements of yaw at impact might occasionally be in error by 1-1/2° and on the average were not in error by more than 0.7°. Some difficulty was caused now and then by fragments projected through the yaw cards in such a manner as to remove part of the outline punched by the bullet. However, the parts of the record removed frequently did not prevent yaw measurement and the possible error due to changing amplitude of yaw at larger yaw card - test plate separations, was considered more serious than the infrequent destruction of the yaw record by a chance fragment.

16. A large number of Aberdeen chronograph records were made with three chronograph screens 2 feet, 18 feet, and 34 feet in front of the test plate. The velocity from the first time interval averaged 40 feet per second higher than the velocity from the second time interval with considerable variation. Differences in velocity readings were observed as high as 100 feet per second and as low as 10 feet per second, with a mean deviation from 40 feet per second ± 15 feet per second. The velocity at impact was deduced by subtracting 20 feet per second from the velocity indicated by the time interval between the second and third screens. The average error in the calculated velocity at impact is believed to have been about ± 15 feet per second and the largest error about ± 30 feet per second.

17. A pronounced yaw effect upon penetration is clearly evident in all of the yaw-velocity diagrams, Plates 2 to 14. Irregularities may be noticed in the case of impacts against the 440 Brinell homogeneous Disston armor. These irregularities consist in impacts at similar values of yaw such that the lower velocity penetrated while the higher velocity did not. Variations of similar magnitude occurred in the Aberdeen Proving Grounds tests, reference (e), and may be seen on Plate 13. On the other hand, no results against softer plate materials were obtained which are not consistent with a regular increase in limit velocity with increasing yaw. The irregular variations in the effect of yaw upon penetration observed in the case of very hard plate are not explainable in terms of errors in measurement of yaw and of velocity. Although breakage of the dart occurred at moderate amounts of yaw even for impacts against 0.7" Duralumin, in general the very hard plates broke the dart at all angles of yaw and the fracture resulted in smaller fragments than was the case for impacts against plates of lower Brinell numbers. Possibly the inconsistent yaw effects found are the result of fracture of the dart starting, in the case of very hard plates, at an earlier time in the penetration cycle, thus increasing the effect upon penetration of any differences in strength of individual darts.

18. Some of the data gathered to illustrate the effect of shooting through thin Duralumin sheets were obtained before a satisfactory material for registering yaw had been discovered. Caliber 30 A.P. bullets were fired at 100 yards through 0.045" 24 ST Duralumin sheet oriented at 0°, 45°, 60°, and 73° obliquities. Yaw was measured by cards of different materials placed about 12 inches behind the penetrations in the Duralumin. Considerable variation in amounts of yaw produced was found probably due

to variation in conditions of yaw at impact. For instance, at 60° obliquity, bullet velocity 2300 to 2400 feet per second, 4, 6, 6, 8 and 14 degrees of yaw were measured for five successive penetrations. In general, the amounts of turning of the bullets were greater for greater obliquities. The average yaw produced at 60° obliquity was approximately 7° at 12 inches behind the Duralumin.

19. A 0.26" face-hardened Diebold armor plate was selected which had a limit at normal incidence of 2000 feet per second by previous determinations. This limit was again measured with a 0.048" 24 ST Duralumin sheet inclined at 60° obliquity, 8 inches and 23 inches in front of the Diebold plate. The impacts are plotted on Plate 14. The slopes of the yaw-limit velocity lines for the "no Dural shield" test and for the "Dural shield at 23 inches" test are believed to be correct within 30 per cent. The corresponding slope for the "Dural shield at 8 inches" test is arbitrarily made similar to that of the neighboring curves. Much more data of this type are needed in order to accurately fix the slopes or to show the amount of indefiniteness of the yaw-limit velocity lines. Some indefiniteness might be expected from variation in the amplitude of yaw introduced by penetration of the Duralumin.

20. All of the gratings tested were constructed with round holes evenly spaced in hexagonal symmetry. The ratio of the weight thickness, e^1, of such a grating to its actual thickness, e, is given by the expression:

$$e^1/e = 1 - 0.907 \ / \ (1 + w/d)^2$$

where w is the web and d is the diameter of the holes. The equivalent steel thickness, e^{11}, is 0.357, e^1 for a Duralumin grating. Results obtained from tests of gratings are tabulated in terms of the shape constants e, w, d, e^1, and e^{11} on Plate 15.

21. The velocity limits stated on Plate 15 are those for which the chances of an impact causing part of the bullet or of the plate to be projected to the rear of the plate, are believed to be less than one in ten. Structures whose protection efficiency depends upon uncontrolled amounts of turning of the bullets give more protection against velocities above the lowest penetrating velocity than do ordinary flat armor plates. This additional protection might be represented by determining a second velocity limit at which 50 per cent of the impacts had more effect than the lowest penetrating velocity. Such a 50 per cent penetration limit has not been determined for the tests in this report, although its usefulness might justify the necessary additional impacts.

22. The darts of the caliber 30 bullets used generally broke during impact. Since dart breakage is involved in the effect of yaw upon penetration in an unknown manner, no estimates of the limit velocities for non-breaking projectiles could be made.

23. An efficiency number K_θ defined in reference (d) was calculated and the results tabulated on Plate 15. For combinations of two plates not parallel, the obliquity, θ, was taken to be the orientation of the second plate with respect to the trajectory of the projectile. The thickness of the first plate was resolved into an equivalent weight thickness parallel to the second plate in computing total weight thickness, e_1, for the calculation of K_θ. The formulas used are:

$$K = (57{,}000/F_1)^2$$

$$F_1^2 = \frac{m}{d^3} V^2 \operatorname{Cos}^2 \theta \, (d/e_1)$$

where (m/d^3) is the mass divided by the diameter cubed of the dart in pounds per cubic foot, V is the limit velocity in feet per second, K_θ is the ratio of the weight of an armor structure to the weight of STS which gives equal protection at the same obliquity. For simplicity $F(e/d, \theta)$ is taken to have the constant value, 57,000, for STS armor.

24. Tests 1 and 2 dispose of the feasibility of using a grating to stop completely a projectile. Tests 3, 5, 6, 7, 8, and 11 are designed to resemble possible impact conditions in which a light grating is used to tumble and deform the projectile. Test 4 demonstrates the efficiency of a flat Duralumin plate for tumbling the projectile. Tests 9 and 10 are divided armor arrangements. The first plate is in one case a grating and in the other case a solid plate of equivalent weight. The efficiency numbers could have been made better by using second plates of hard bullet-proof armor rather than of STS. However, for purposes of comparison, a large supply of rather uniform material was needed and was available only in the soft type armor plate.

CONCLUSIONS

25. Tests of several thicknesses of STS armor plate and of Duralumin plates show that limit velocities increase about five times as fast with angle of yaw of the bullet as with angle of obliquity of the armor plate. Unlike STS plate for which the merit coefficient remains about constant, hard bullet-proof plate shows a considerable merit coefficient increase with angle of obliquity, but the percentage change in limit velocity with yaw is no greater than that for STS plate. Thus limit velocities for hard armor plate increase with angle of yaw about once to twice as fast as with angle of obliquity.

26. Samples of 17 ST Duralumin, STS armor, and hard homogeneous armor had comparable yaw effects upon penetration. One sample of STS armor hardened to Brinell 370 showed the largest rate of increase of limit velocity with angle of yaw, 2.3 per cent. The behavior of hardened STS armor was also found to be exceptional in previous tests

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wherein the merit coefficient for this material showed the largest measured rate of increase with angle of obliquity.

27. Rather meager data indicate yaw has a much smaller effect upon penetration in the case of face-hardened armor than was found for the other materials investigated. There is also some evidence in the data that limit velocities increase more rapidly with yaw at large angles of yaw than at small angles of yaw.

28. A few impacts against 1/8" STS armor and 1/8" Disston armor did not appear to break the dart for angles of yaw of 6° and less. The dart was recovered intact in the case of one partial penetration of 1/2" Disston armor at nearly zero yaw. Generally, however, evidence of breakage of the dart was found and this phenomenon of bullet fracture probably restricts the interpretation of results of these yaw studies more than any feature. The extension of these results to larger obliquities and other bullets is complicated by the uncertain extent to which the yaw effects measured depend upon dart breakage.

29. Since several degrees of yaw at impact are not uncommon even when using a Mann barrel at 100 yards, the data in this report are of significance with respect to accurate plate testing. From these data one may calculate that at a velocity of 2000 feet per second or more, a plate limit based upon a partial penetration with 3° yaw may be in error by 45 to 90 feet per second, due to the effect of yaw upon penetration. Some experimental data of interest with respect to this are shown on Plate 13, where data from tests at Aberdeen Proving Ground are plotted. Less than 3° yaw is not measurable on some types of yaw cards and the data on Plate 13 show no yaw measurements of one or two degrees. Presumably, the seven impacts listed as having zero yaw had amounts of yaw ranging from zero to nearly three degrees. The velocity difference between the lowest penetrating velocity and the highest non-penetrating velocity among the seven "zero" yaw impacts was 50 feet per second. The scatter of results due to bullet fracture is probably very small at normal incidence and zero yaw.

30. Measurements on 1/8" to 1/2" thicknesses showed the F coefficients increasing from 52,000 to 56,000. This result might mean the previously found constancy of F coefficients for STS armor was due to some greater average yaw affecting tests at low velocities. However, all of the thin plates of STS armor tested at the Naval Research Laboratory have been obtained by splitting and grinding from old Carnegie plates of 3/4" to 1-1/4" thickness, obtained from the Naval Proving Grounds. It is possible that the plate chosen for manufacture of the 1/8" and 1/4" thicknesses was of poor ballistic quality compared with the plate from which the 1/2" sample was obtained.

31. Data gathered to illustrate the effect upon bullets of passage through thin sheets of Duralumin of thicknesses comparable to those used on aircraft, are not as yet definite in a quantitative sense. Considerable yaw produced by passage through 0.048" 24 ST

Duralumin at 60° can be measured at several feet behind the impact. The data plotted on Plate 14 show a direct measurement of the effect of a thin shielding plate of Duralumin upon limit velocity of a Diebold face-hardened armor plate. The slopes of the yaw-limit velocity lines are not well determined by the data. One might expect the effect of initial yaw of the bullet at impact would be masked by the additional yaw introduced by the Duralumin. In such an event the yaw-limit velocity line would be a poorly determined line perpendicular to the velocity axis. On Plate 14, the data, although very scattered, seem better represented by nearly parallel lines showing about 0.6 per cent rate of increase of limit velocity with angle of yaw. The turning effect of the Duralumin upon the bullets shows up in the increasing limit with increasing separation of the plates and in the greater F coefficient obtained at the 23-inch separation. This F coefficient was computed including the weight of the Duralumin. When the weight of the Duralumin is omitted, the Diebolt plate appears to have an F coefficient of 80,000 for normal impacts with zero yaw. Thus the necessary weight of armor computed neglecting the effect of passage through a Duralumin fuselage covering 0.048" thick might be 20 per cent too high.

32. For the Duralumin gratings tested, effects of the initial yaw of the bullet were completely masked up to about 10 degrees of yaw. All of the gratings partially stripped the jackets of the caliber 30 A.P. bullets and introduced large amounts of turning. During tests of Item 3, Plate 15, it was noticed that the bullet was turned more by striking an old perforation than by passage through unused portions of the grating. This suggested use of gratings with larger holes which were indeed found to be more effective.

33. The results shown on Plate 15 are affected by the ballistic quality of the backing plate used and should be evaluated in terms of the ballistic properties of the backing plates. The 0.27" STS backing plate had a penetration coefficient of 52,000. The penetration coefficients of the .253" and .26" backing plates have yet to be measured and cannot be given in this report. The most effective Duralumin gratings tested had ratios of hole diameter and plate thickness of from .8 to 1.0 and web thickness greater than 0.1". Although the data show the effectiveness of gratings to be very much influenced by design, the efficiencies measured were in no case greater than that of a solid Duralumin plate, Item 4, Plate 15, tested under the same conditions. Further tests of gratings are planned in which optimum design features will be sought and Duralumin of higher physical properties used.

SUMMARY

34. Three investigations directly related to light armor for aircraft were described in this report: the effect of yaw upon penetration, the effect upon bullets of penetrating very thin Duralumin sheets, and the use of shielding structures in the form of gratings. Data illustrating these topics are still in the process of collection.

Methods of these investigations are, however, described and preliminary results of interest are shown.

35. An effect of yaw upon penetration of about 1.4 per cent limit velocity increase per degree yaw was found for samples of 17 ST Duralumin, STS armor plate and hard homogeneous armor. The largest yaw effect was measured using a plate of STS armor hardened to Brinell 370. The smallest measured yaw effect was obtained on a sample of 1/4" face-hardened armor. It is shown that apparent differences in plate quality or bullet quality of 50 feet per second in plate testing may be due to several degrees of yaw of the bullets at impact.

36. If armor is spaced back inside the fuselage of an aircraft, bullets may tumble before striking the armor, due to penetrating a Duralumin sheet at large obliquity. The effect of a shielding Duralumin sheet at 60 degrees obliquity and 23 inches separation on the limit of a typical bullet-proof plate at normal incidence is shown to be more than 200 feet per second. There is a gain in weight efficiency even when the resolved weight of the Duralumin is included with that of the armor plate.

37. The efficiency of a light grating used as the first plate of a divided armor structure depends considerably upon design. Certain design improvements have been ascertained. On account of the very large effectiveness of solid shielding plates, it is still uncertain whether gratings or solid plates are better as first members of a divided armor structure.

EFFECT OF YAW UPON PENETRATION AT NORMAL INCIDENCE.

Material	Thick-ness	Limit Velocity	Per Cent Increase of Limit per Degree Yaw	Merit Coefficient at Zero Yaw
17 ST Duralumin	0.352"	1100	0.95	57,000
17 ST Duralumin	0.704"	1615	1.4	59,000
17 ST Duralumin	1.052"	2020	1.4	60,400
17 ST Duralumin	1.405"	2460	1.0	63,500
STS Armor	0.125"	990	1.5	51,000
STS Armor	0.246"	1415	1.6	52,000
STS Armor	0.50"	2160	1.2	56,000
STS Armor (hardened to Brinell 370)	0.37"	1980	2.3	59,000
Disston Homogeneous Armor*	0.127"	1020	1.2	52,000
Disston Homogeneous Armor*	0.25"	1615	1.3	59,300
Disston Homogeneous Armor	0.50"	2600	1.3	67,000
Diebold Face-hardened Armor	0.25"	2000	0.6	71,700
Face-hardened Armor**	1/4"	2110	0.7	< 77,000

* Ground down from 1/2". Other Disston plates rolled to size show F coefficients above 67,000.

** Measured at Aberdeen Proving Ground. This plate may have been as thick as 0.265".

Plate 1

EFFECT OF YAW UPON PENETRATION AT NORMAL INCIDENCE.

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Disston Homogeneous Armor	0.50"	2600	1.3	67,000
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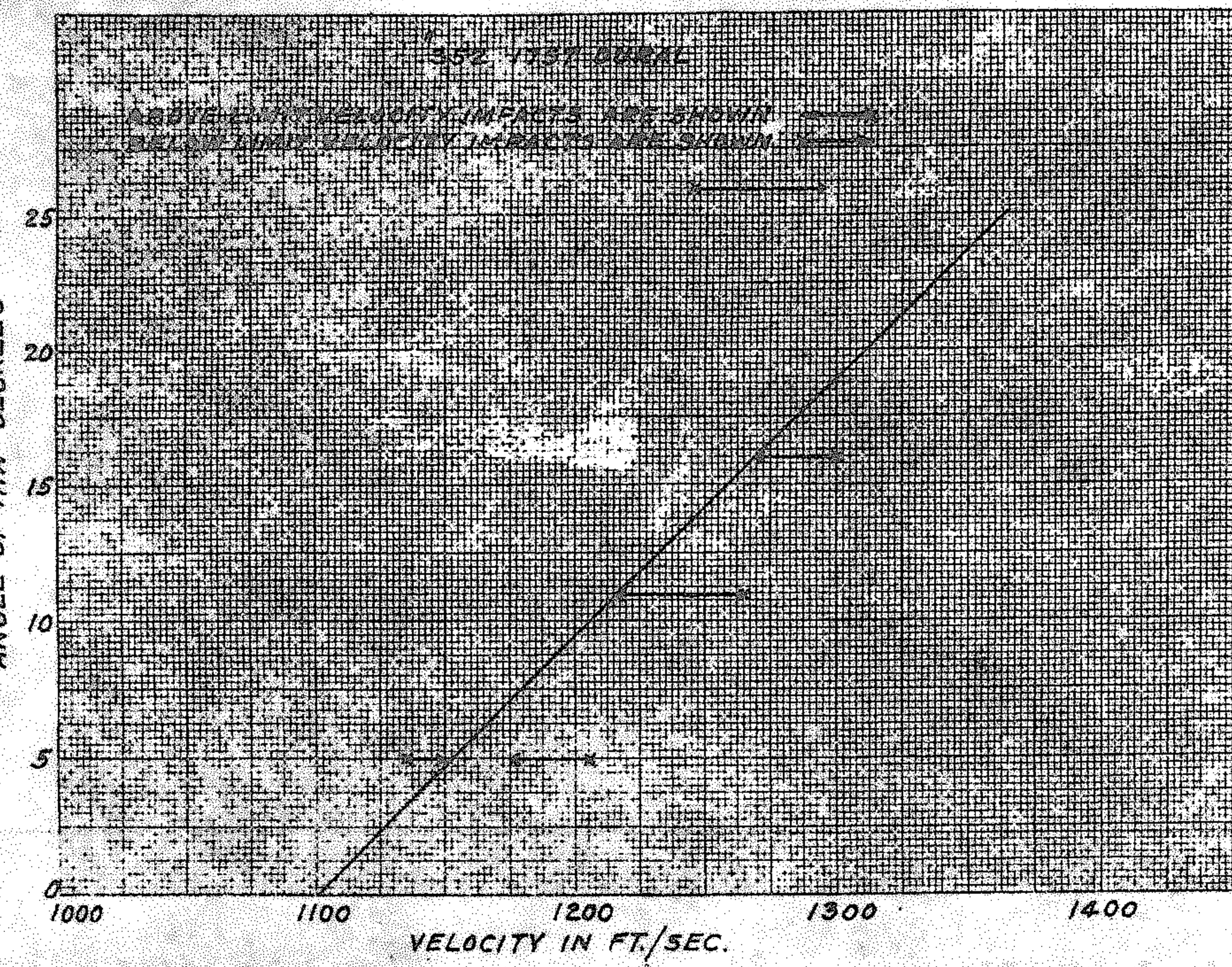
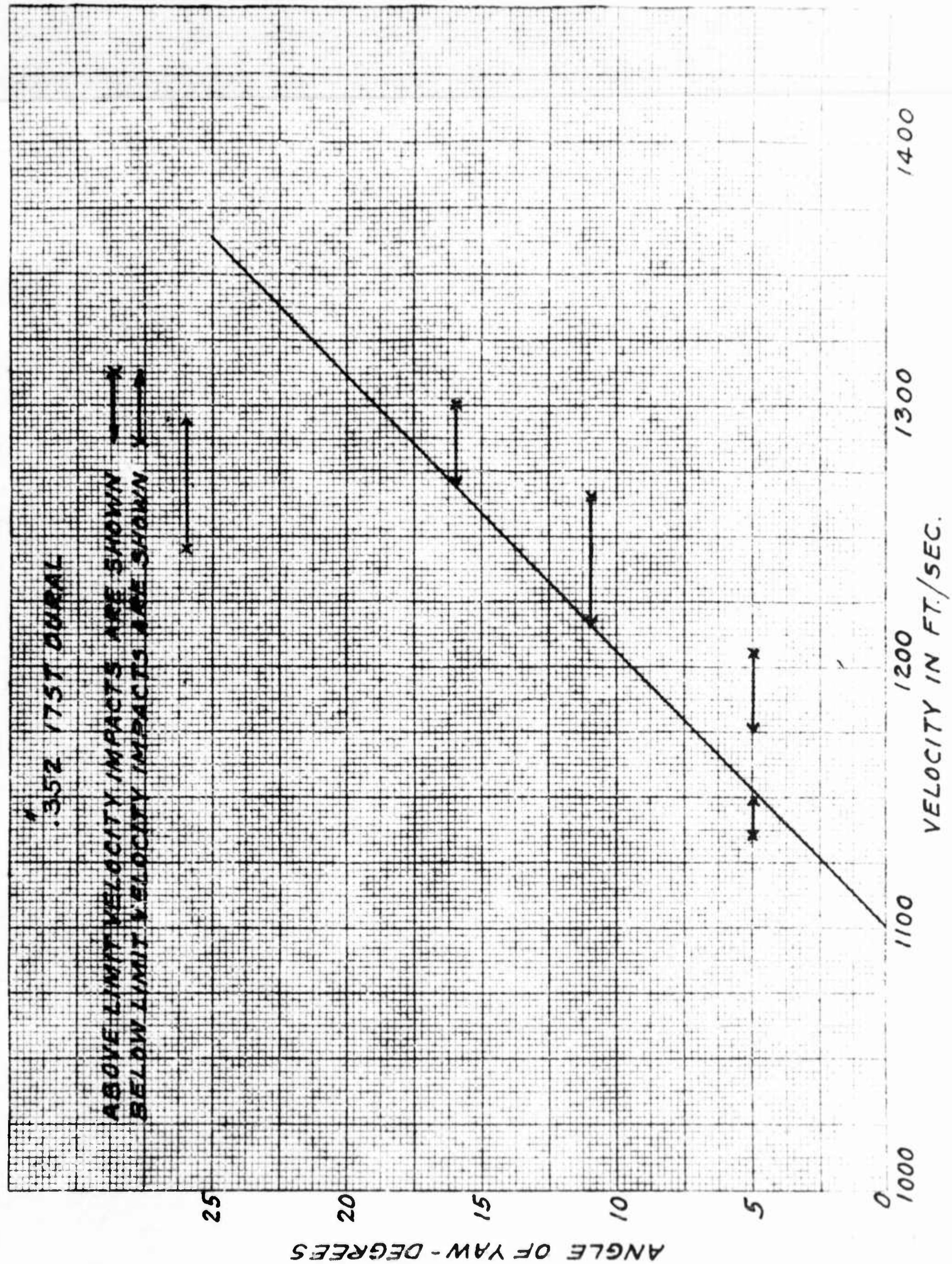


PLATE 2



.352 175T DURAL
ABOVE LIMIT VELOCITY IMPACTS ARE SHOWN
BELOW LIMIT VELOCITY IMPACTS ARE SHOWN
VELOCITY IN FT./SEC.
1000
1100
1200
1300
1400
ANGLE OF YAW - DEGREES
0
5
10
15
20
25

PLATE 2

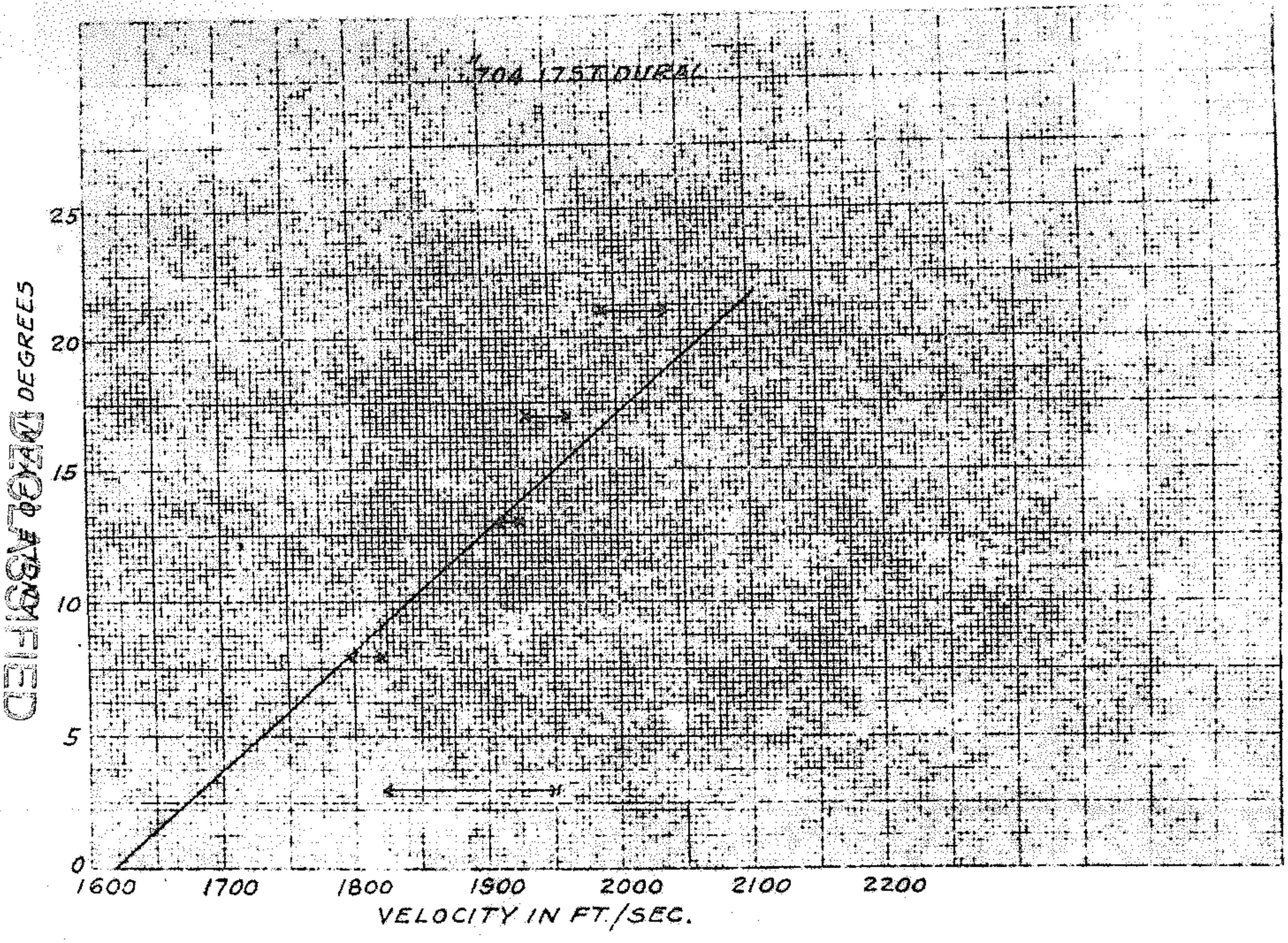
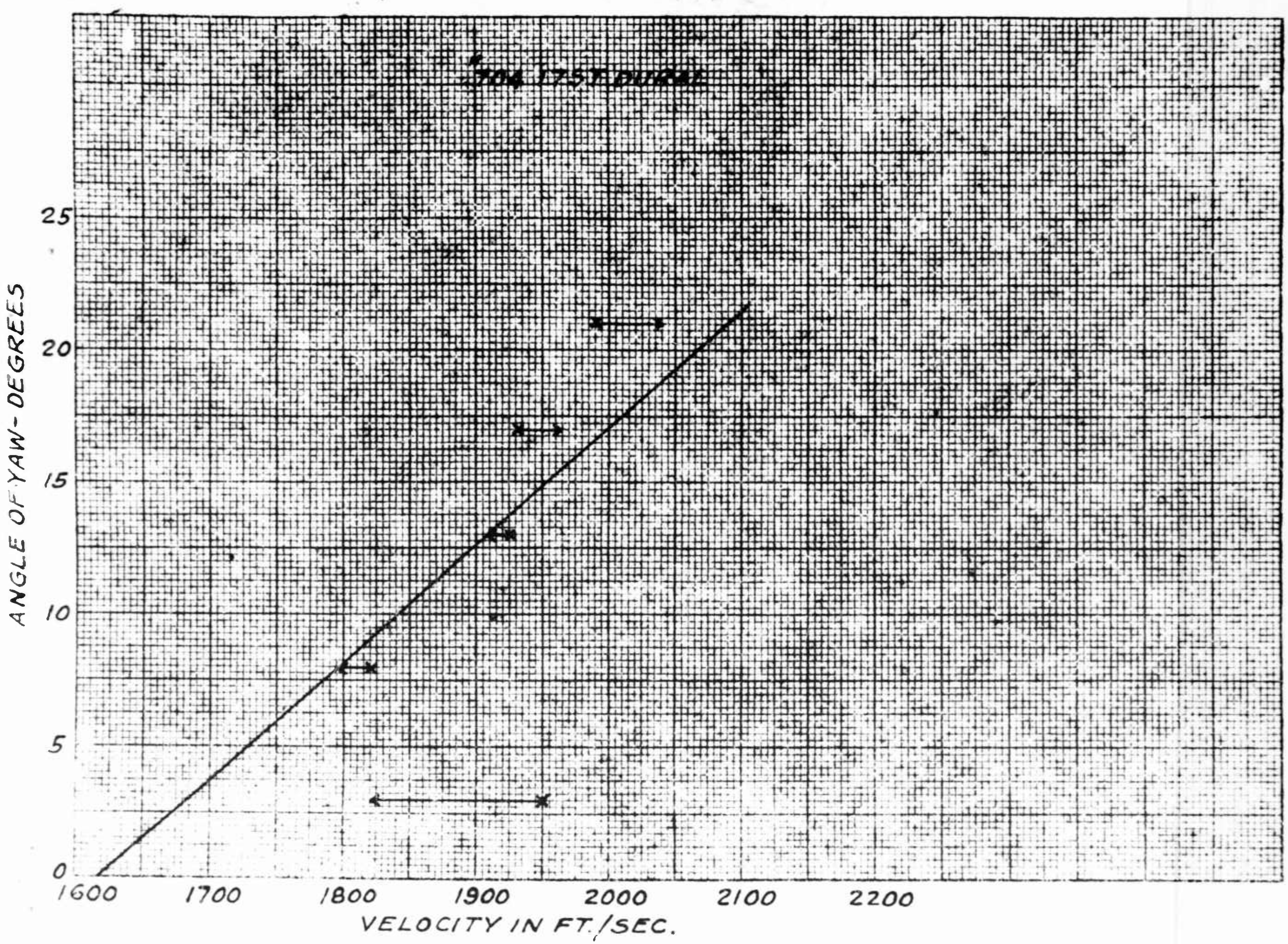

704 17ST DURAL
ANGLE OF YAW DEGREES
0
5
10
15
20
25
1600
1700
1800
1900
2000
2100
2200
VELOCITY IN FT./SEC.

PLATE 3

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.

N. R. L. 31A



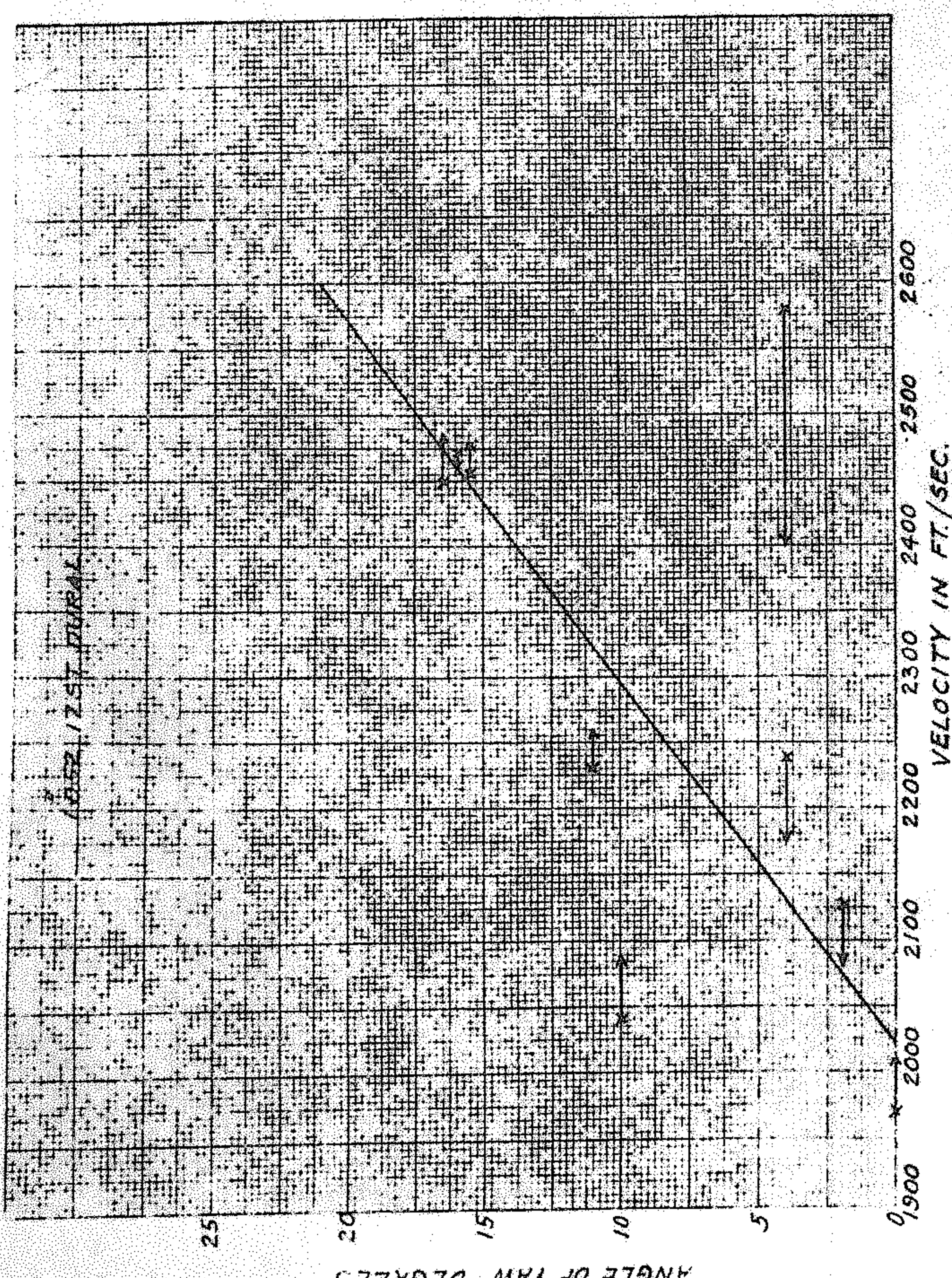
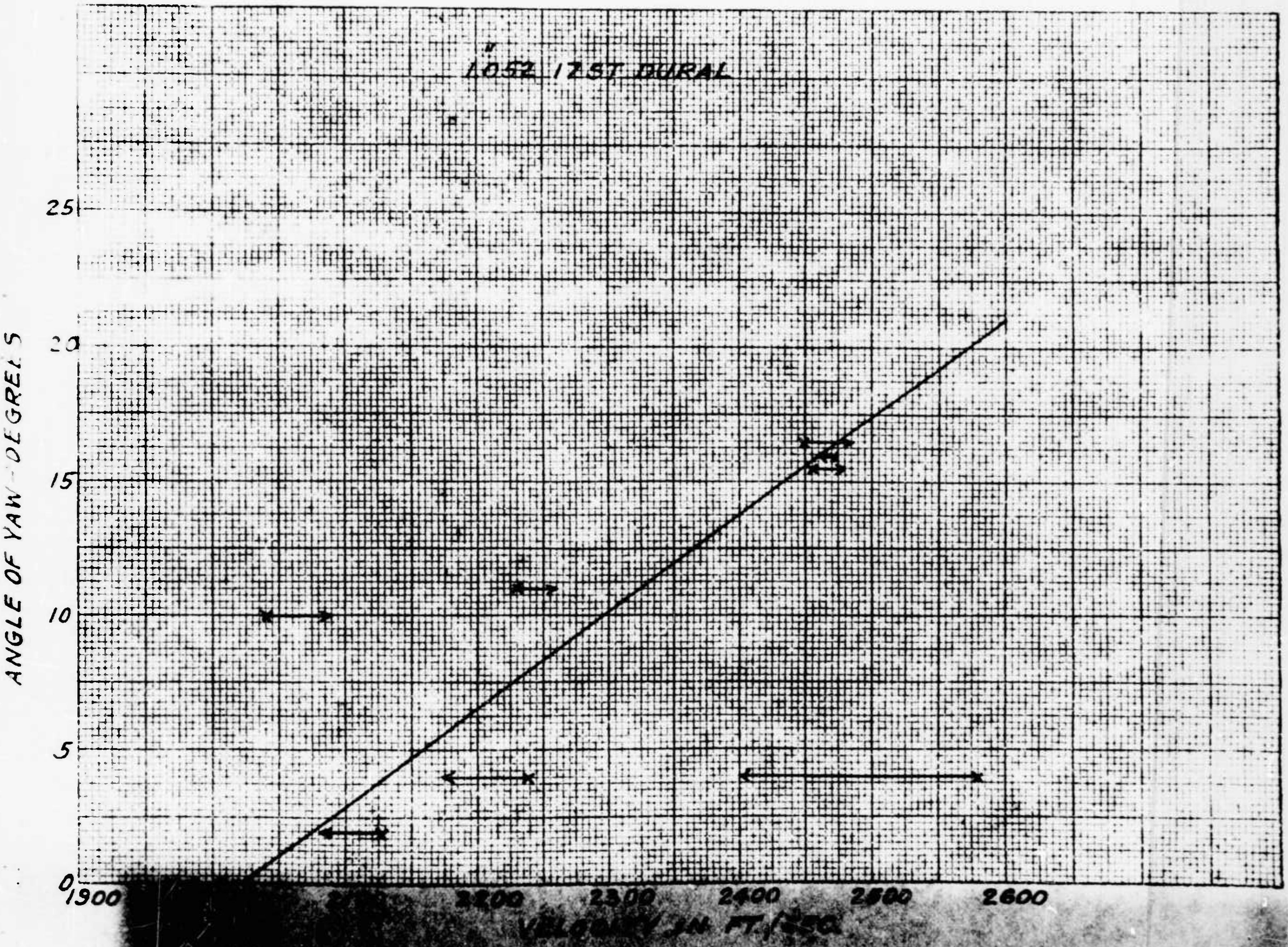

.052 17ST DURAL
VELOCITY IN FT./SEC.
1900
2000
2100
2200
2300
2400
2500
2600
ANGLE OF YAW DEGREES
0
5
10
15
20
25

PLATE 4



.1052 17ST DURAL
ANGLE OF YAW - DEGREES
25
20
15
10
5
0
1900
2200
2300
2400
2500
2600
VELOCITY IN FT./SEC.

PLATE 4

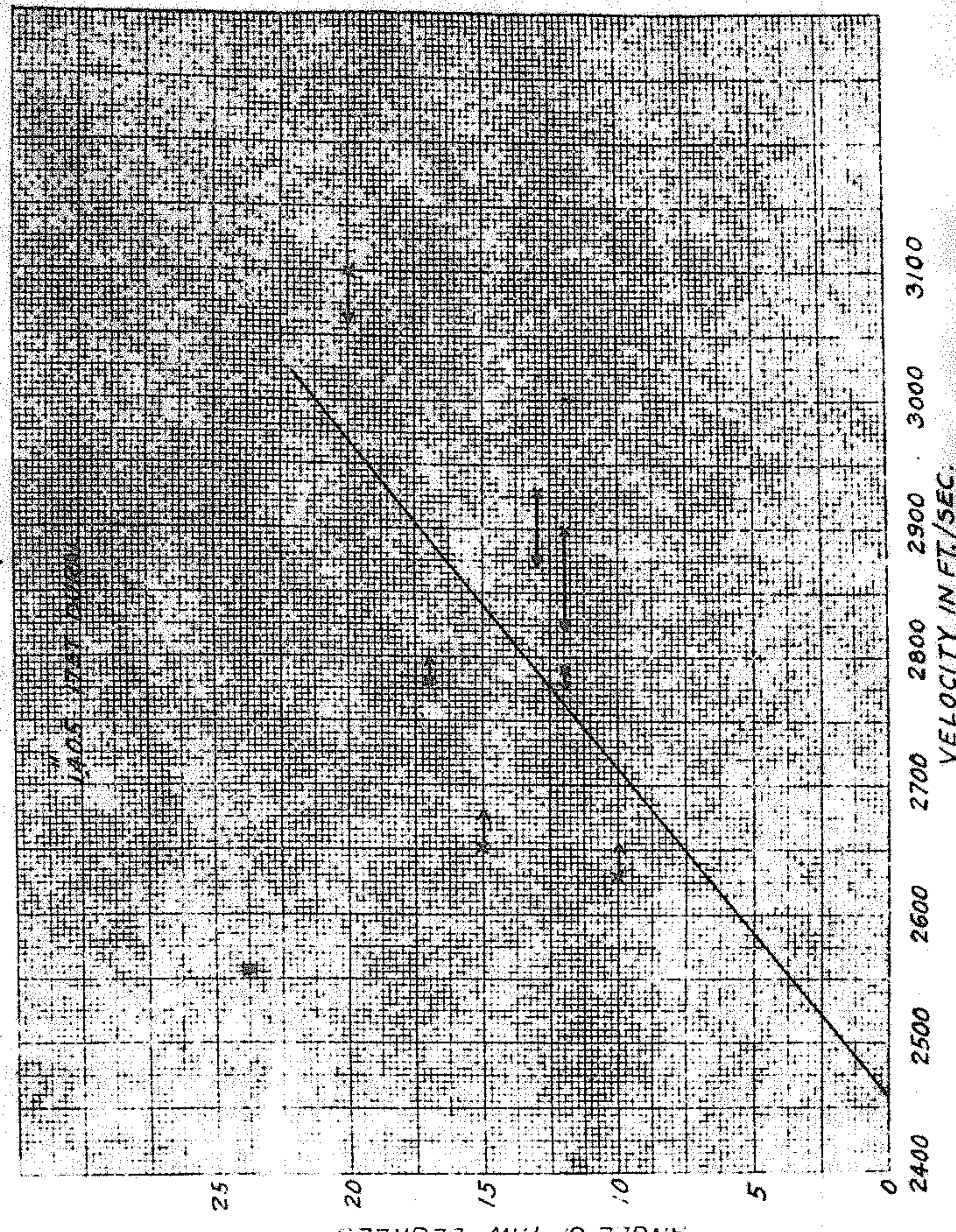

VELOCITY IN FT./SEC.
2400
2500
2600
2700
2800
2900
3000
3100
ANGLE OF YAW – DEGREES
0
5
10
15
20
25

PLATE 5

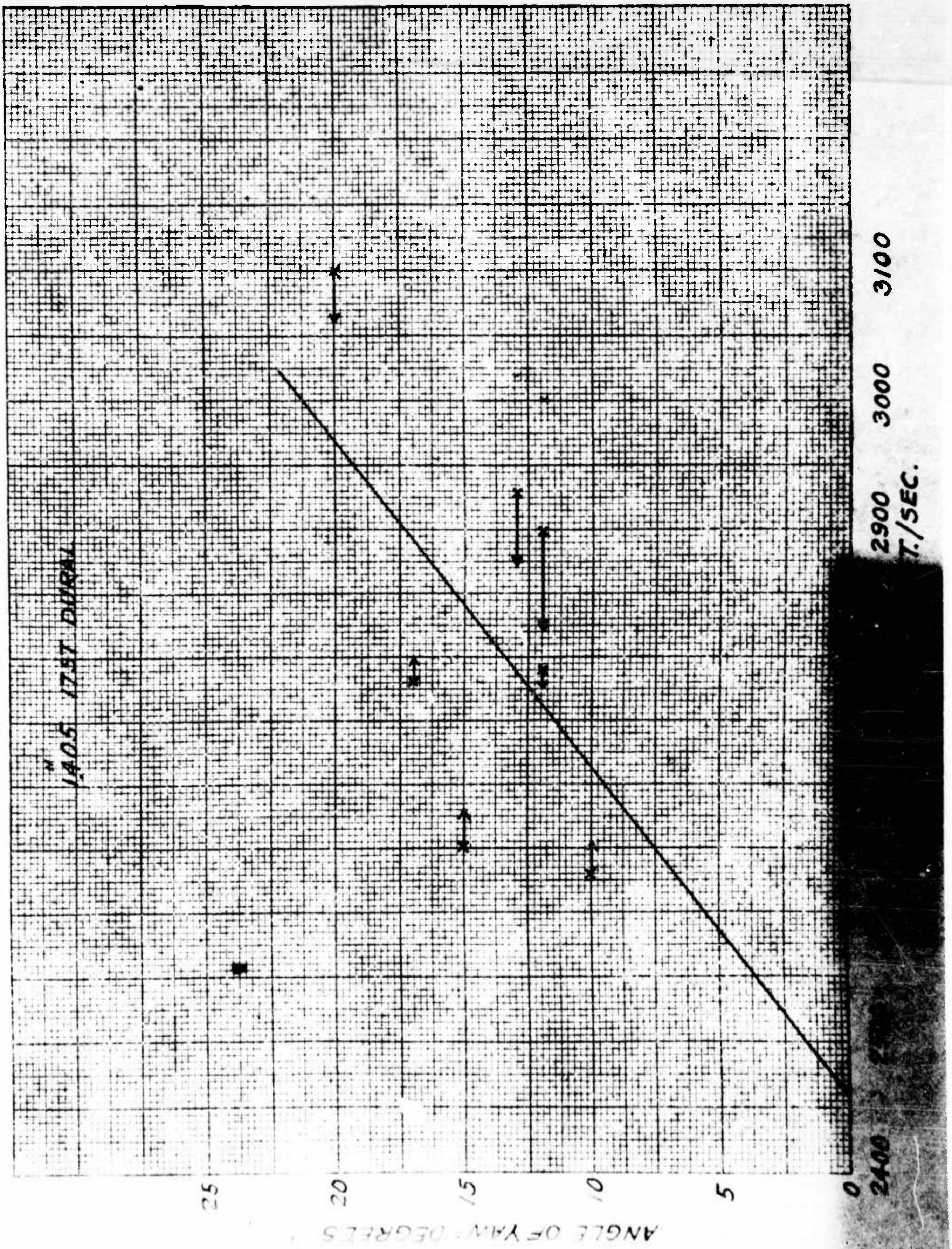
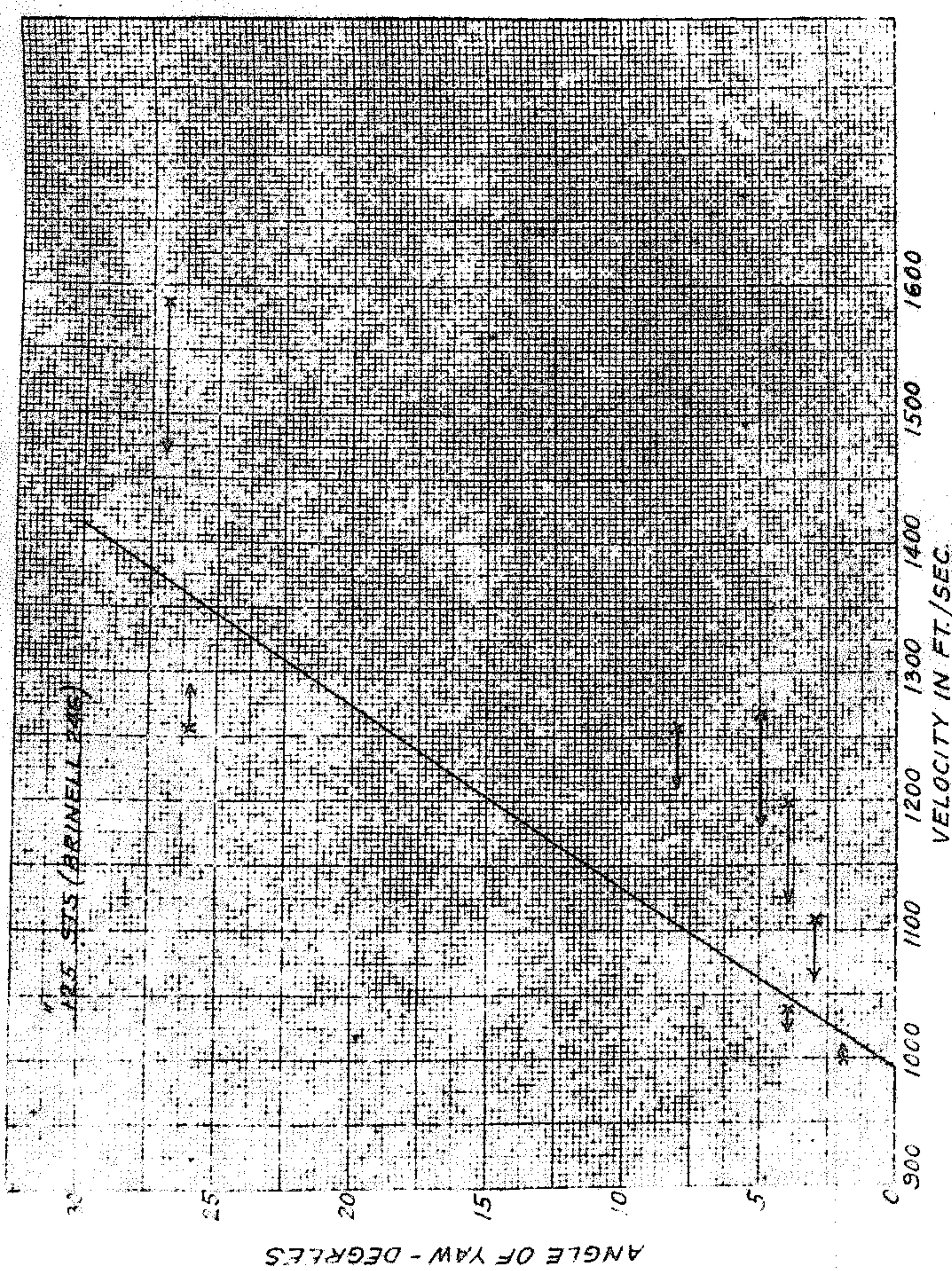

1.405" 17ST DURAL
ANGLE OF YAW - DEGREES
0
5
10
15
20
25
2400
2900
3000
3100
T./SEC.

PLATE 5

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.

DATE



DECLASSIFIED

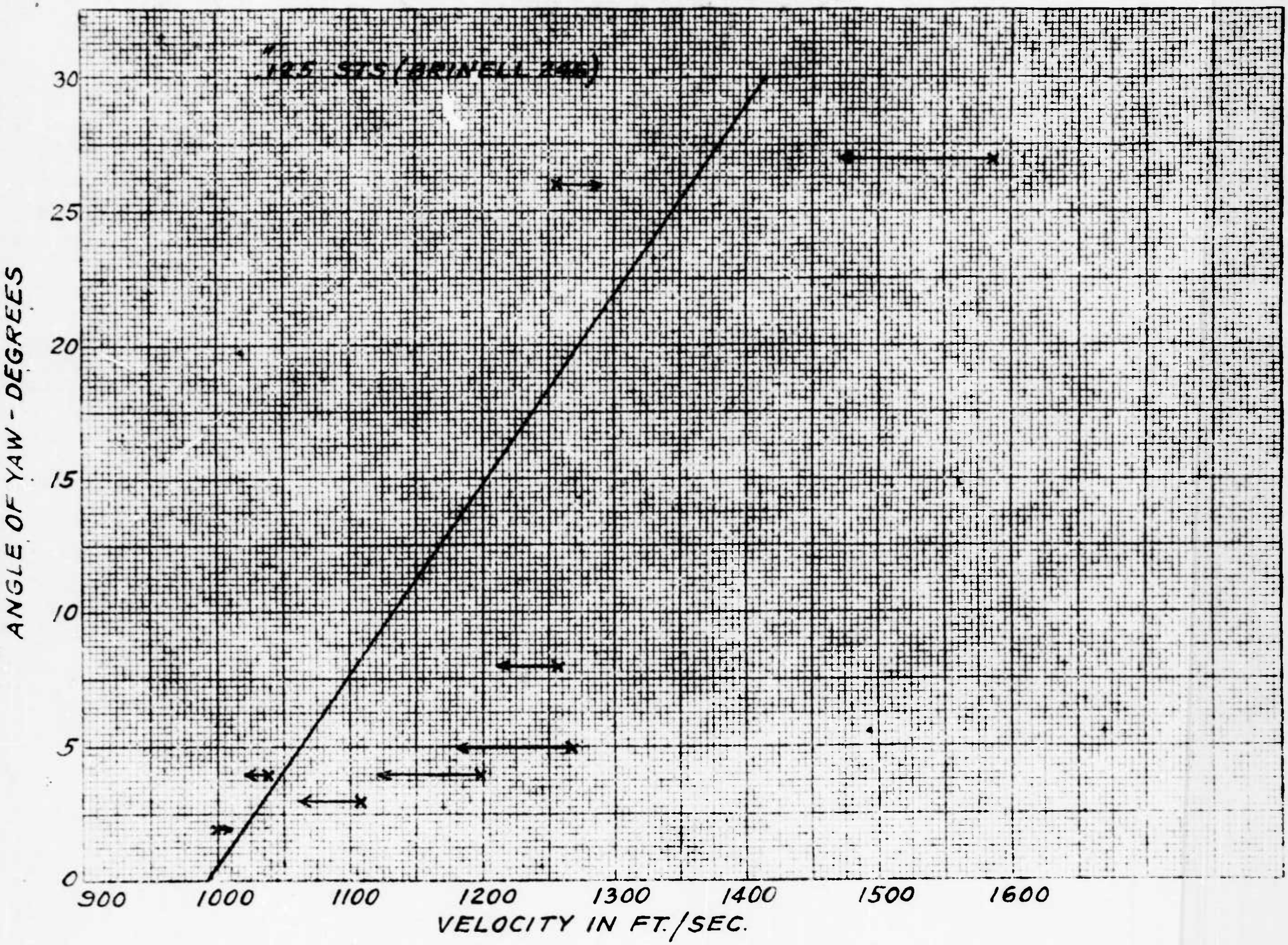

1.25" STS (BRINELL 246)
ANGLE OF YAW - DEGREES
0
5
10
15
20
25
30
900
1000
1100
1200
1300
1400
1500
1600
VELOCITY IN FT./SEC.

PLATE 6

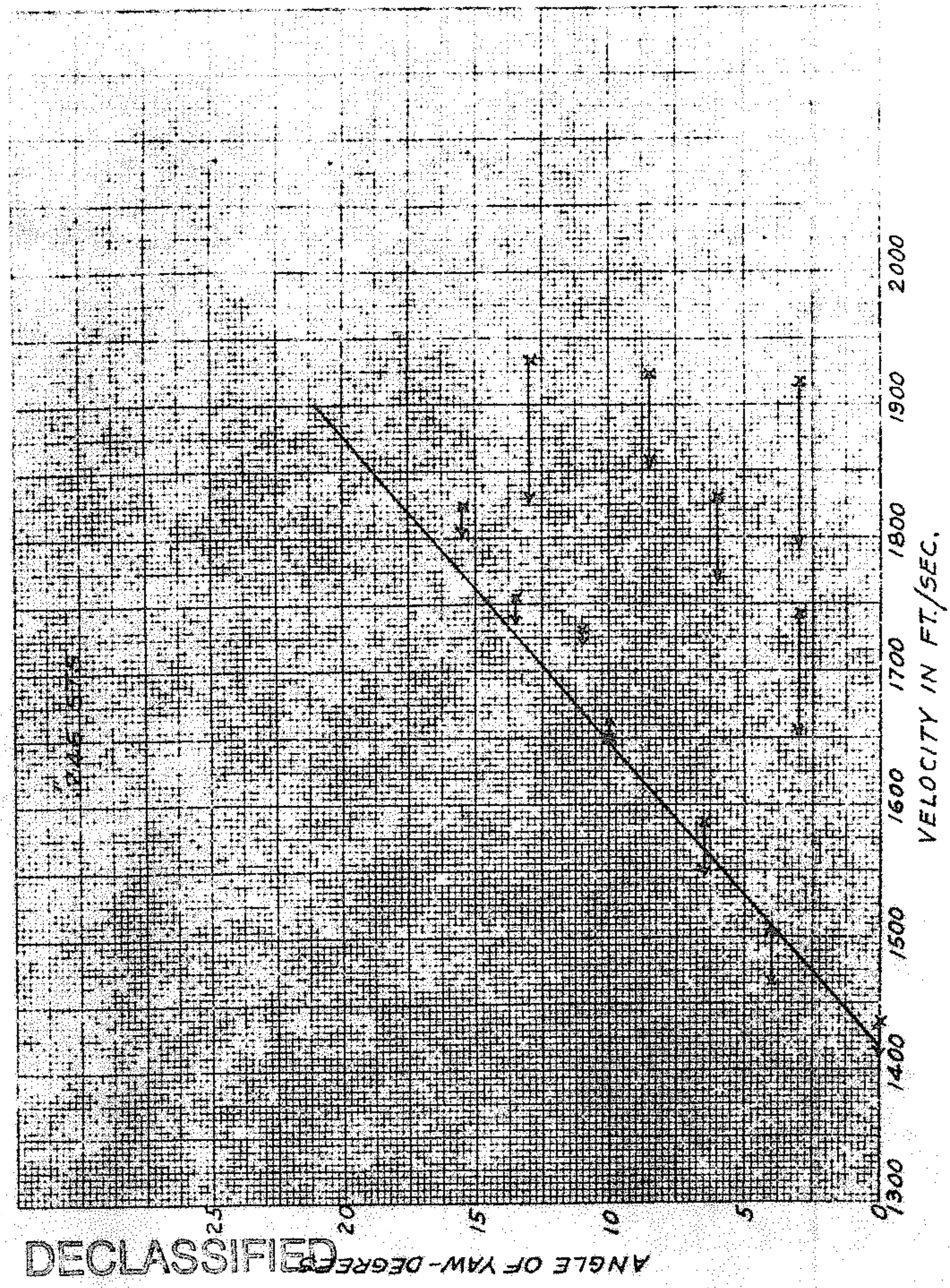

VELOCITY IN FT./SEC.
1300
1400
1500
1600
1700
1800
1900
2000
ANGLE OF YAW - DEGREES
0
5
10
15
20
25

PLATE 7

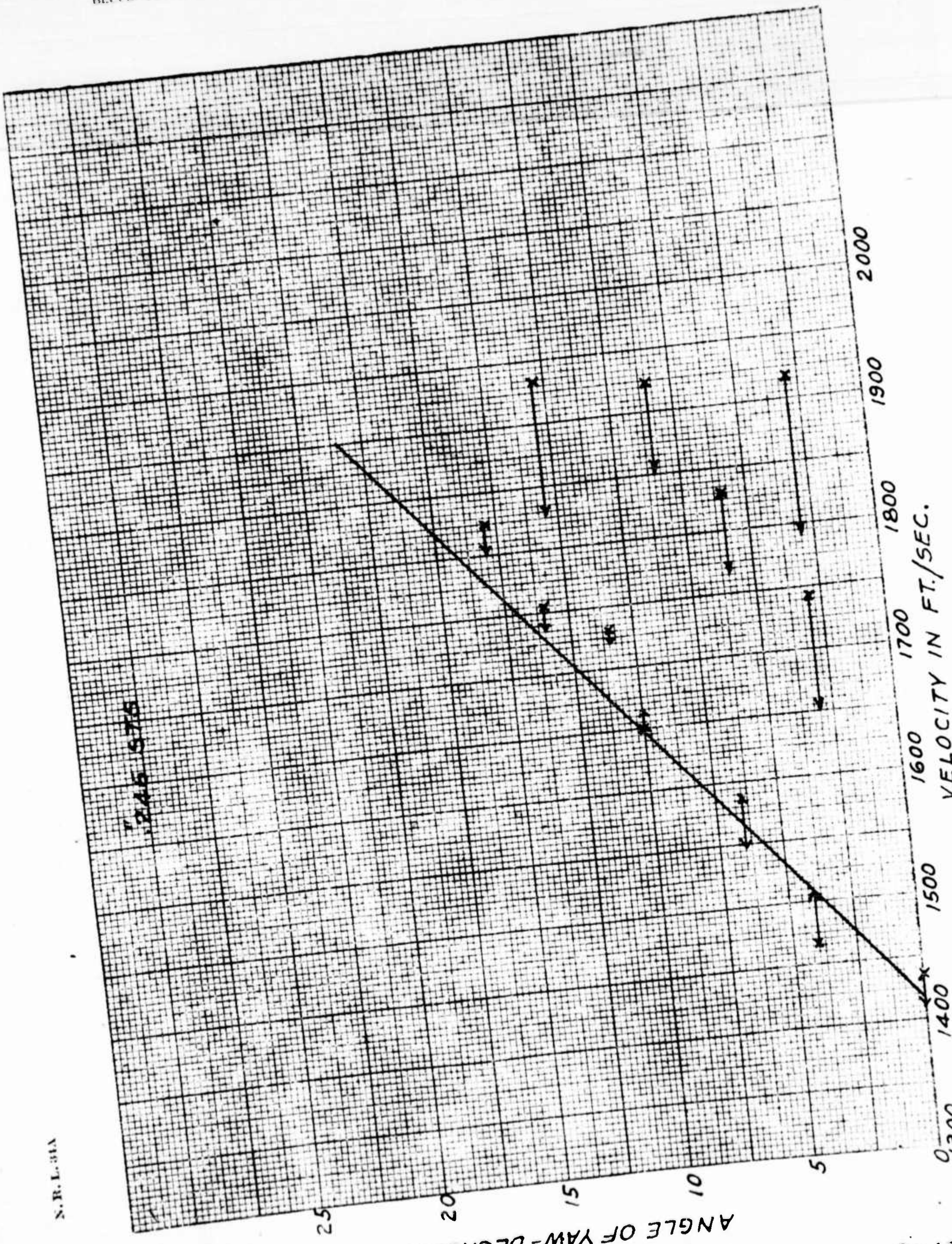
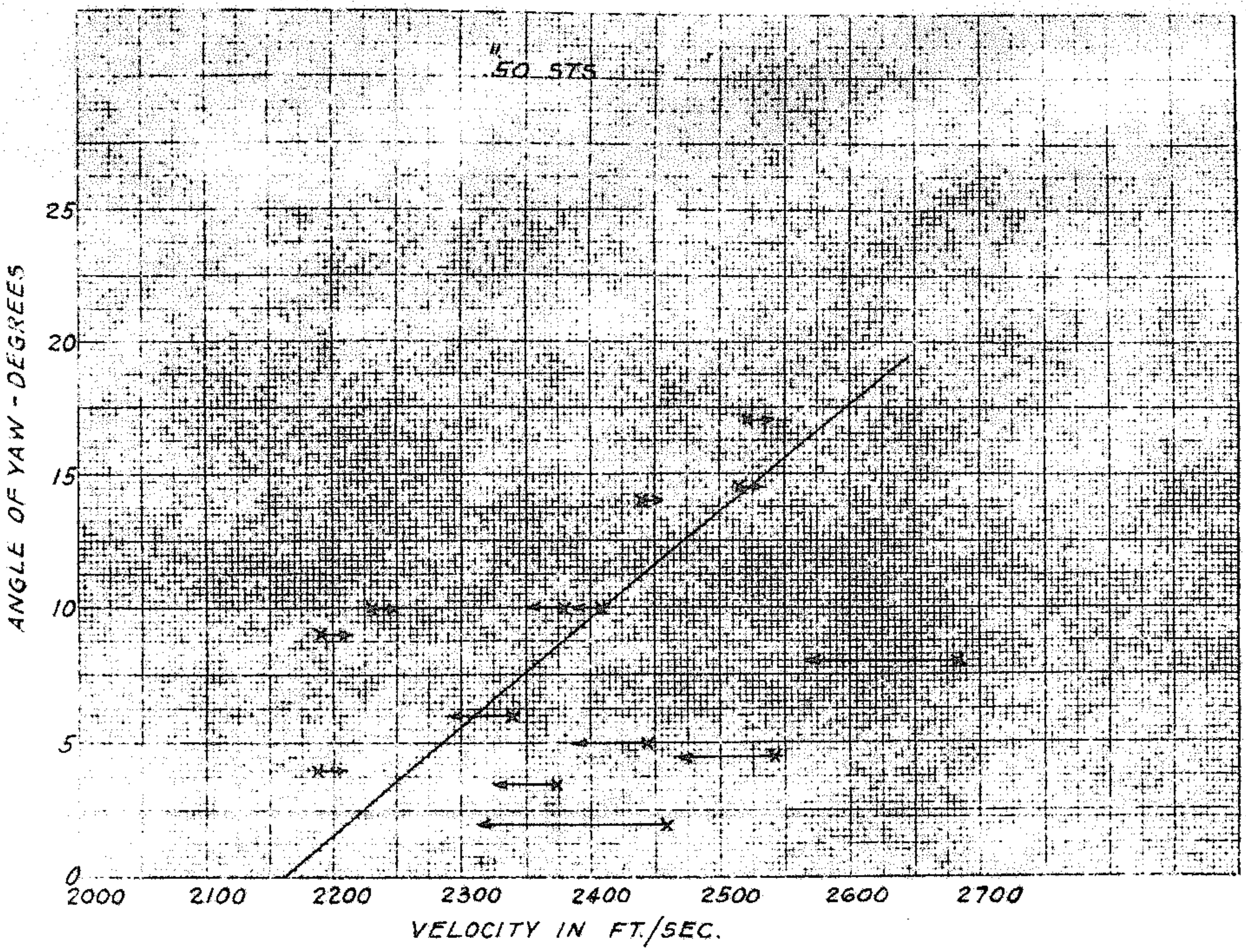

VELOCITY IN FT./SEC.
1300
1400
1500
1600
1700
1800
1900
2000
ANGLE OF YAW-DEGREES.
0
5
10
15
20
25

PLATE 7



DECLASSIFIED

PLATE 8

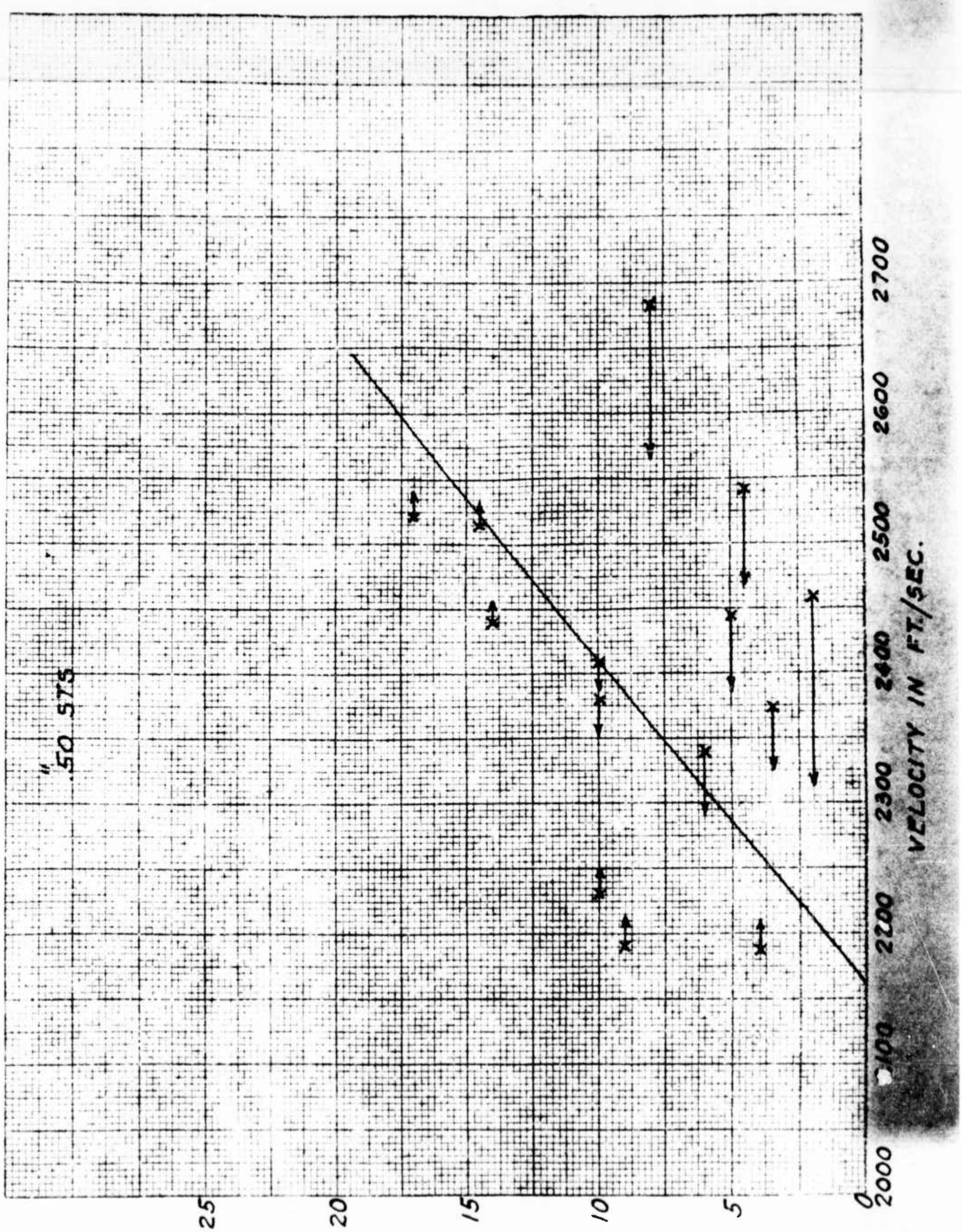
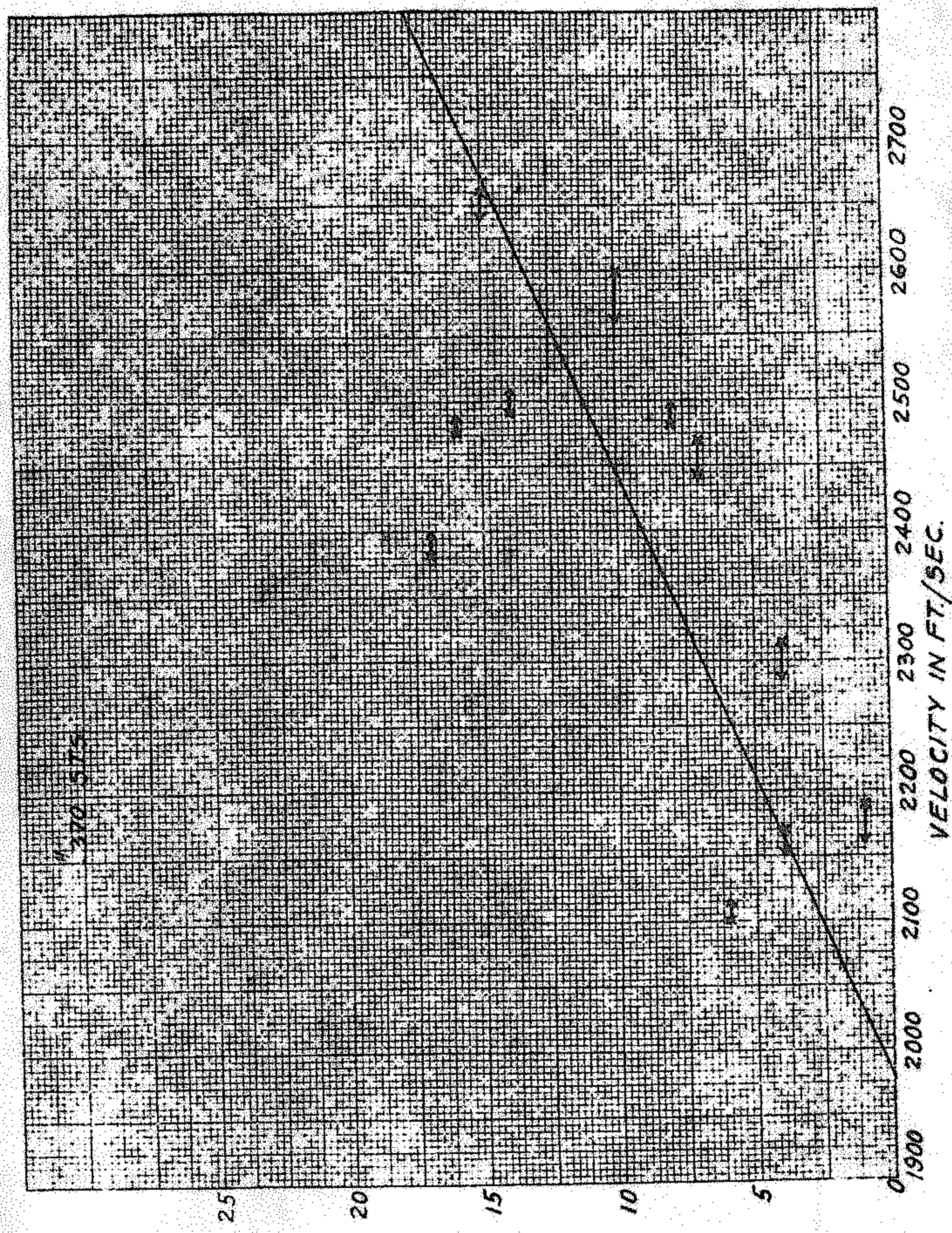
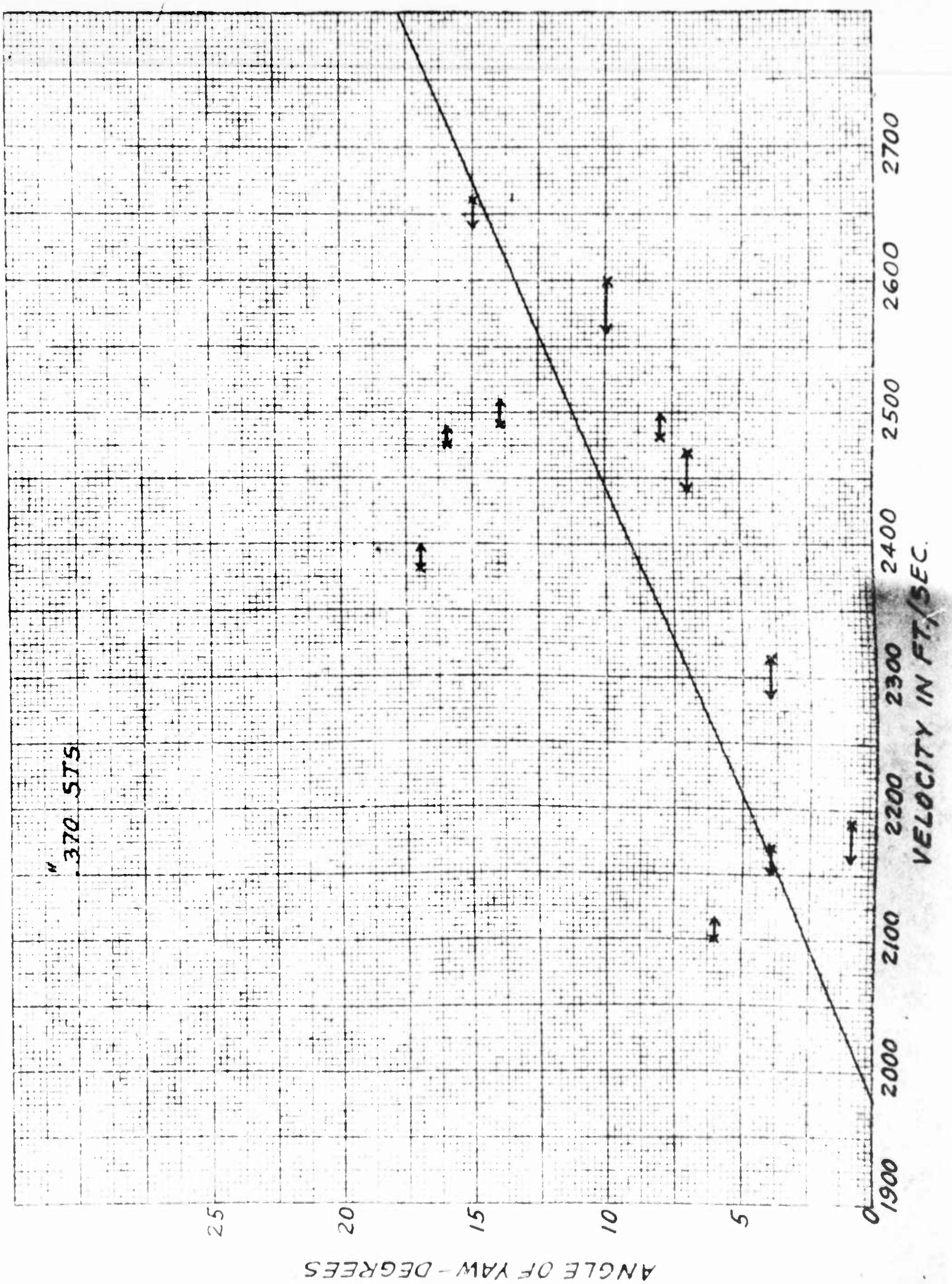

.50 STS
VELOCITY IN FT./SEC.
2000
2100
2200
2300
2400
2500
2600
2700
ANGLE OF YAW - DEGREES
0
5
10
15
20
25

PLATE 8


1900
2000
2100
2200
2300
2400
2500
2600
2700
VELOCITY IN FT./SEC.
0
5
10
15
20
25
ANGLE OF YAW - DEGREES
370 STS

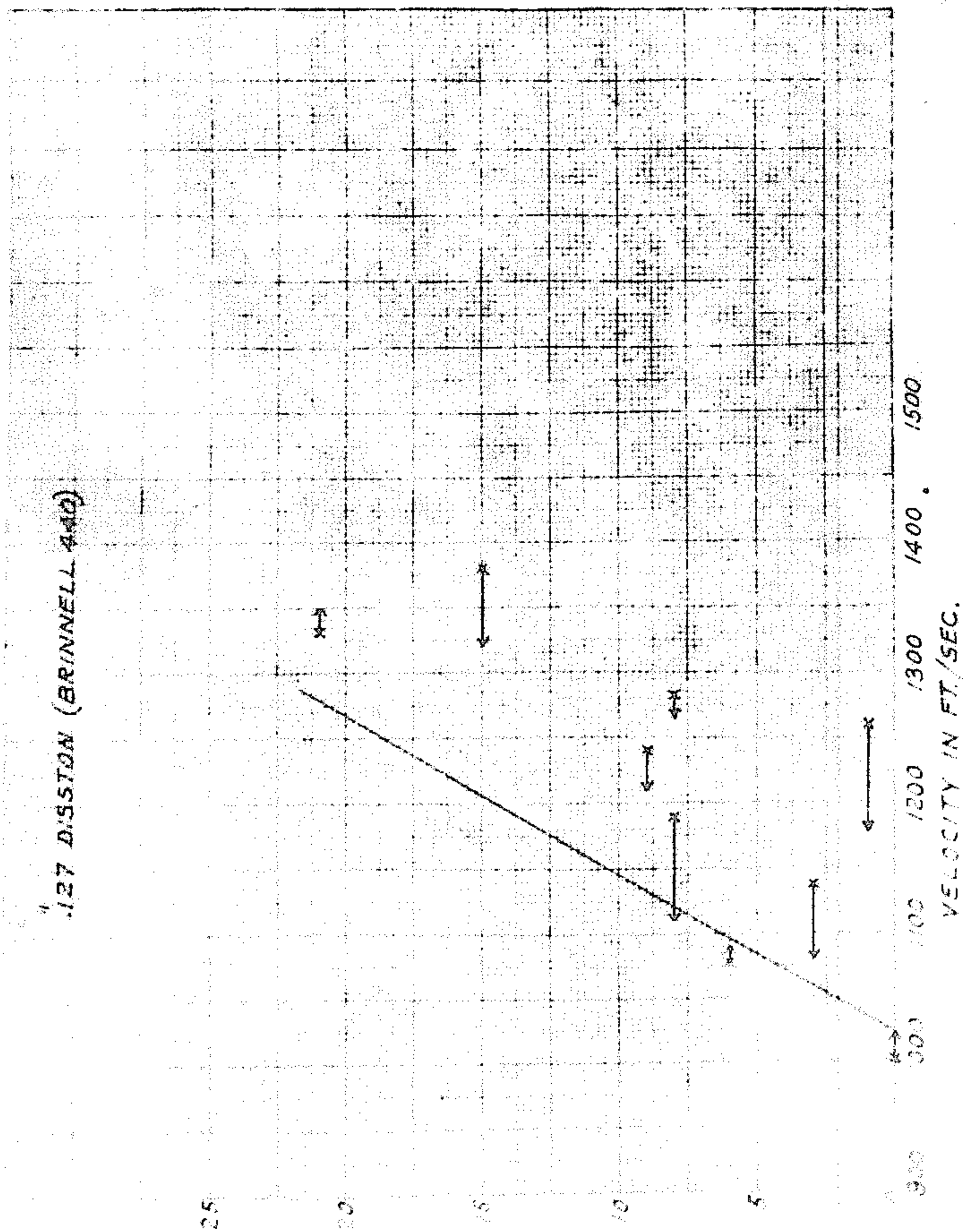
PLATE



".370 STS
VELOCITY IN FT./SEC
1900
2000
2100
2200
2300
2400
2500
2600
2700
ANGLE OF YAW - DEGREES
0
5
10
15
20
25

PLATE 9

DECLASSIFIED



DECLASSIFIED

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.

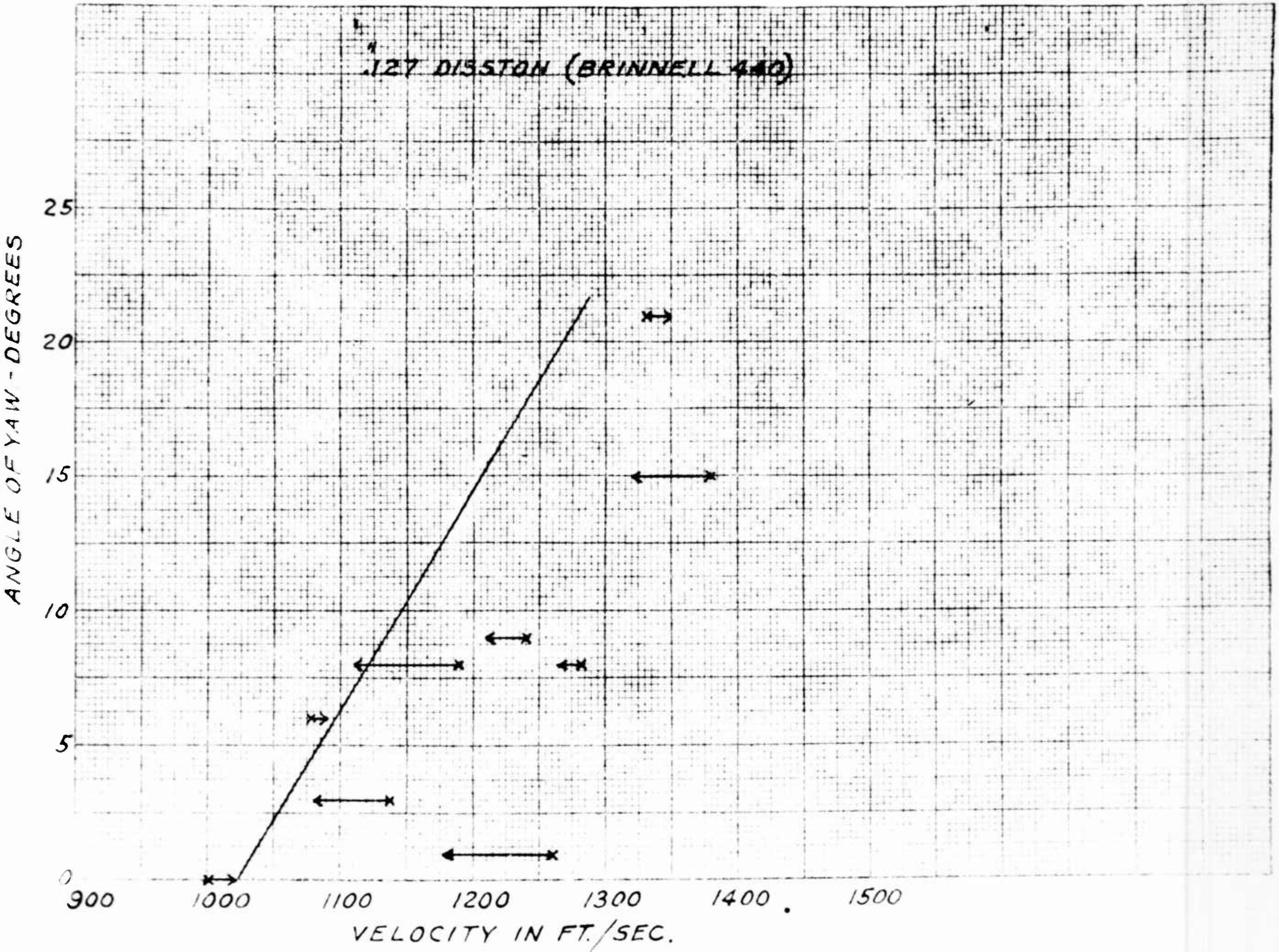
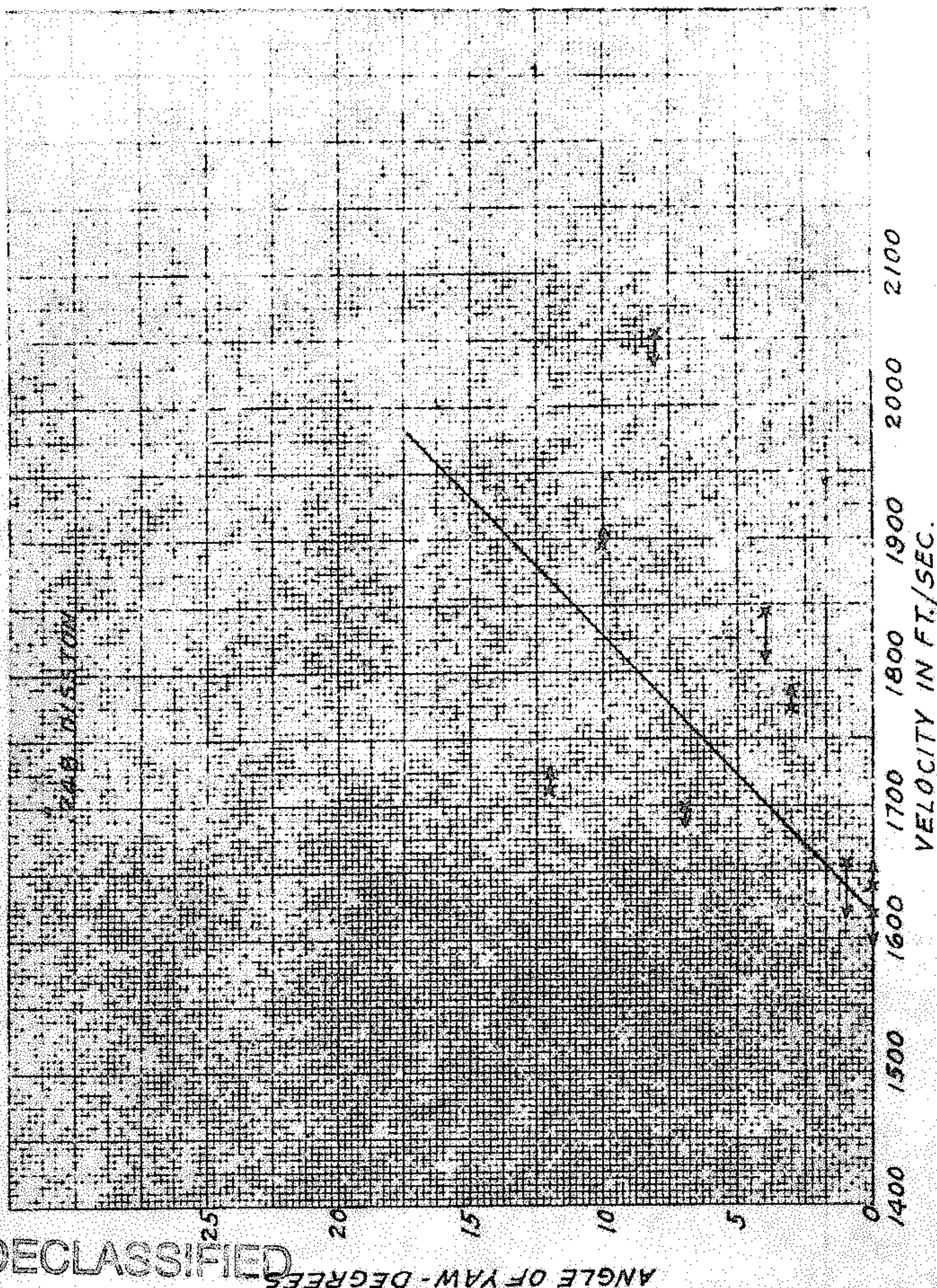
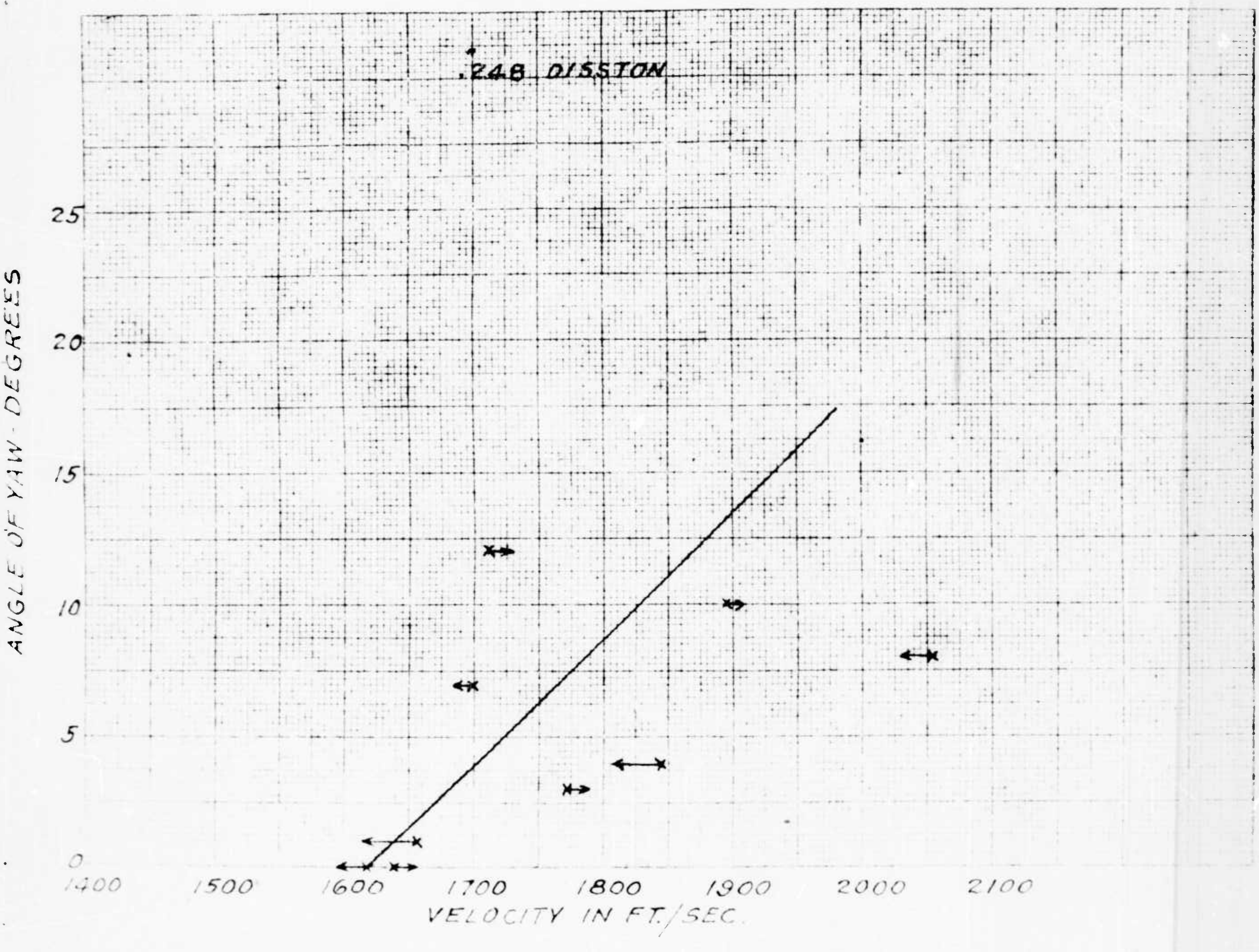


PLATE 10

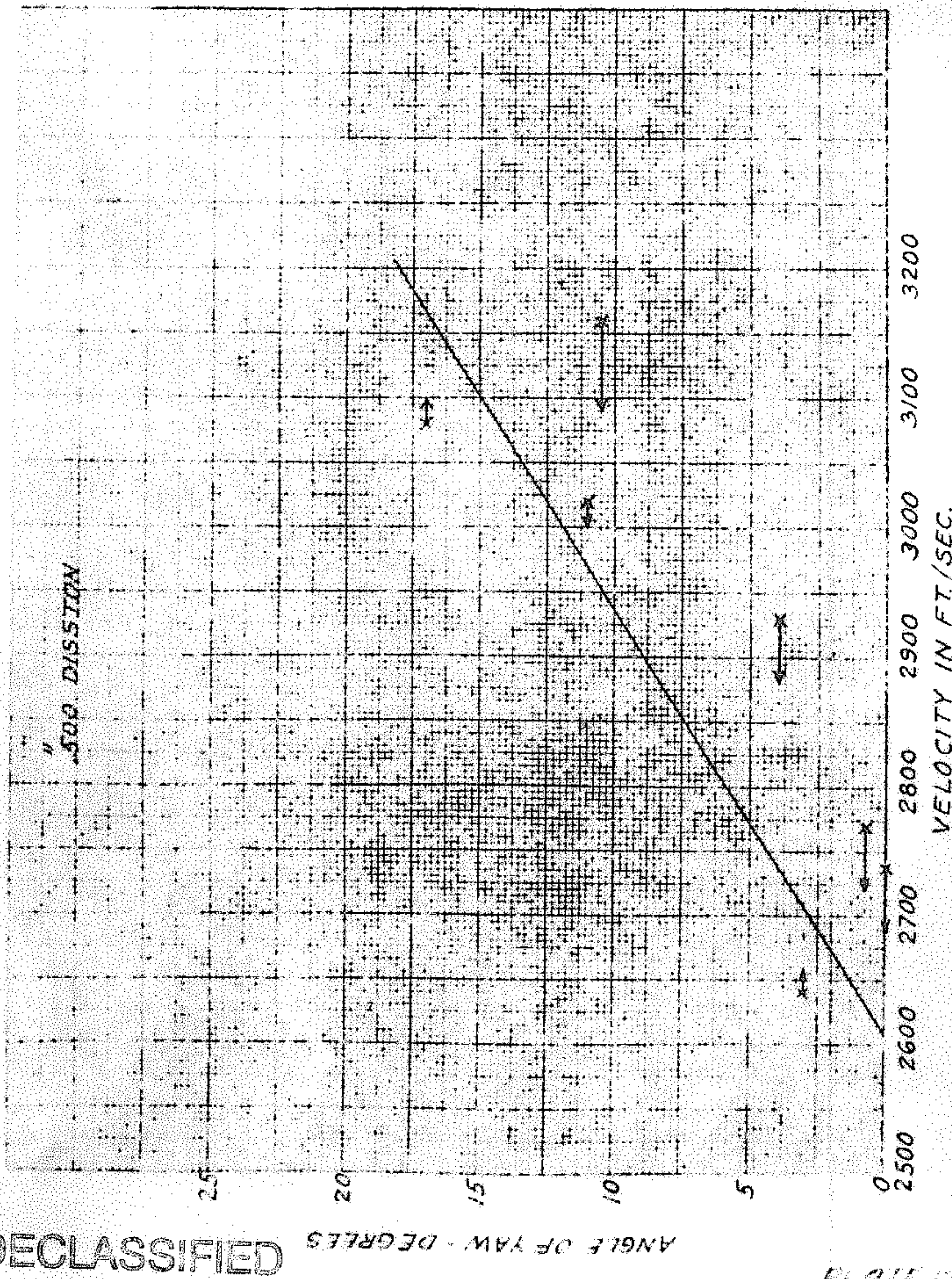


VELOCITY IN FT./SEC.
1400
1500
1600
1700
1800
1900
2000
2100
ANGLE OF YAW - DEGREES
0
5
10
15
20
25

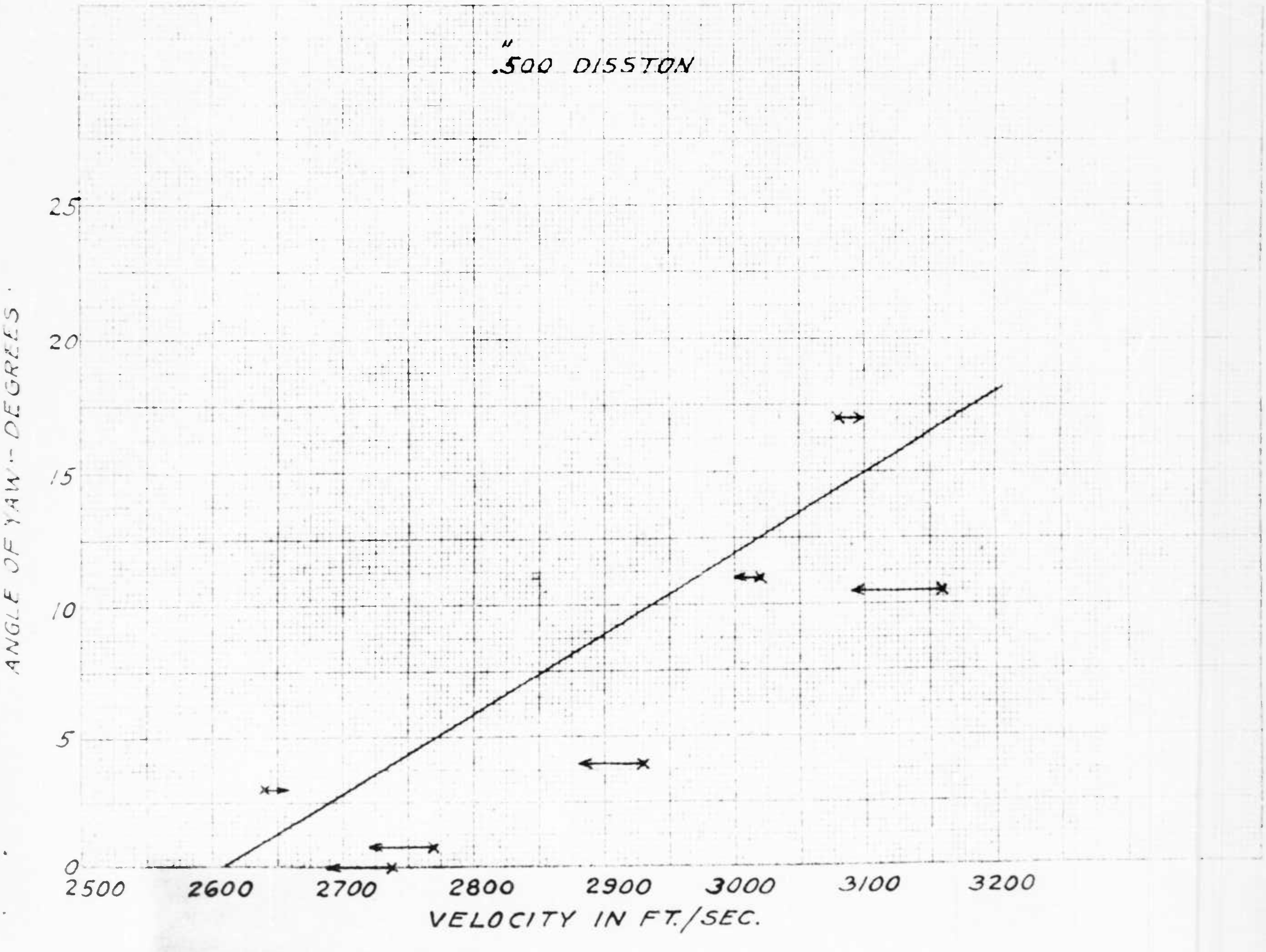
IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.



PLATE

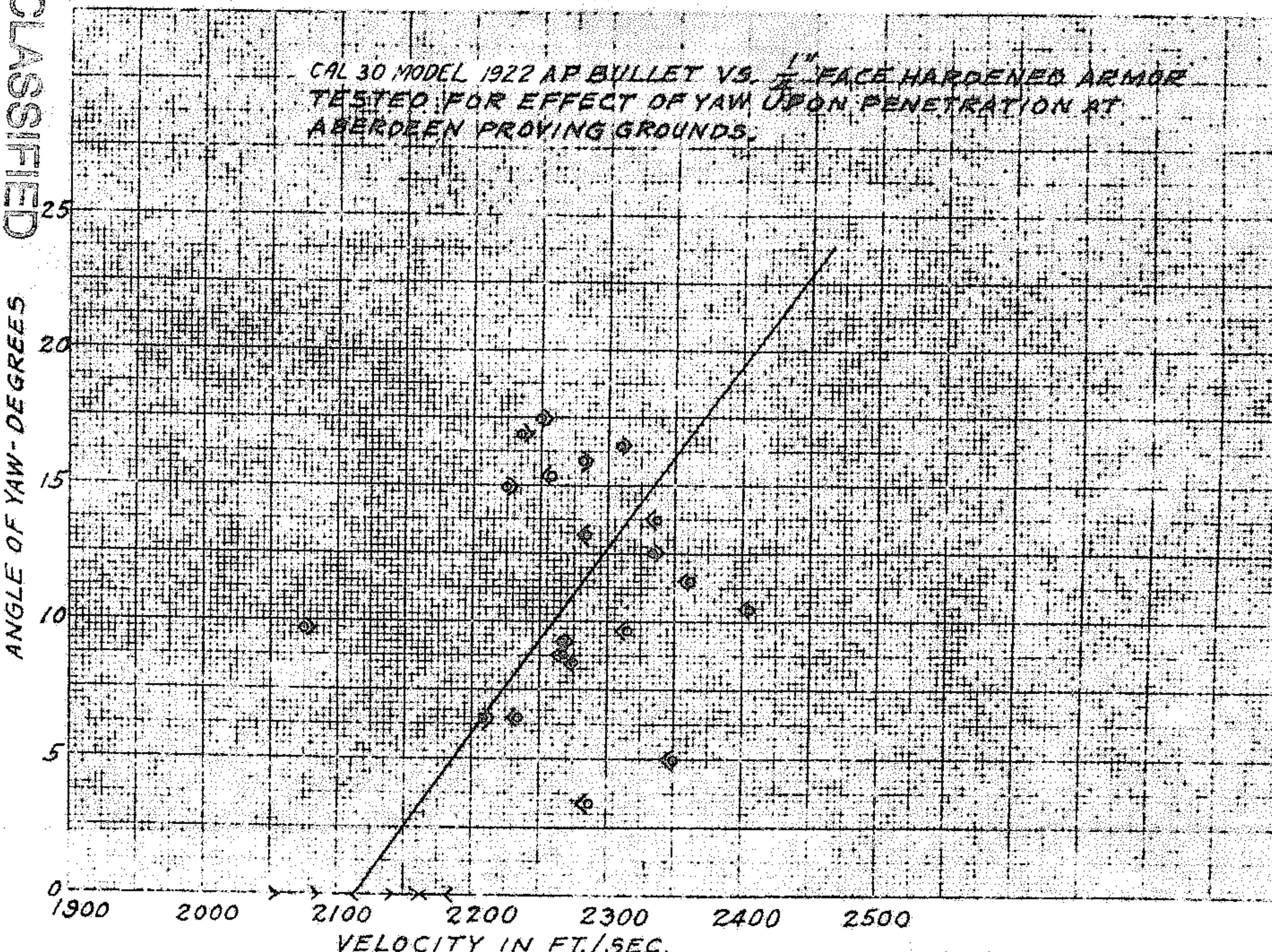


.500" DISSION
VELOCITY IN FT./SEC.
2500
2600
2700
2800
2900
3000
3100
3200
0
5
10
15
20
25
ANGLE OF YAW - DEGREES



.500" DISSTON
ANGLE OF YAW - DEGREES
25
20
15
10
5
0
2500
2600
2700
2800
2900
3000
3100
3200
VELOCITY IN FT./SEC.

PLATE 17



CAL 30 MODEL 1922 AP BULLET VS. 1/4" FACE HARDENED ARMOR
TESTED FOR EFFECT OF YAW UPON PENETRATION AT
ABERDEEN PROVING GROUNDS.
ANGLE OF YAW - DEGREES
0
5
10
15
20
25
1900
2000
2100
2200
2300
2400
2500
VELOCITY IN FT./SEC.

PLATE 13

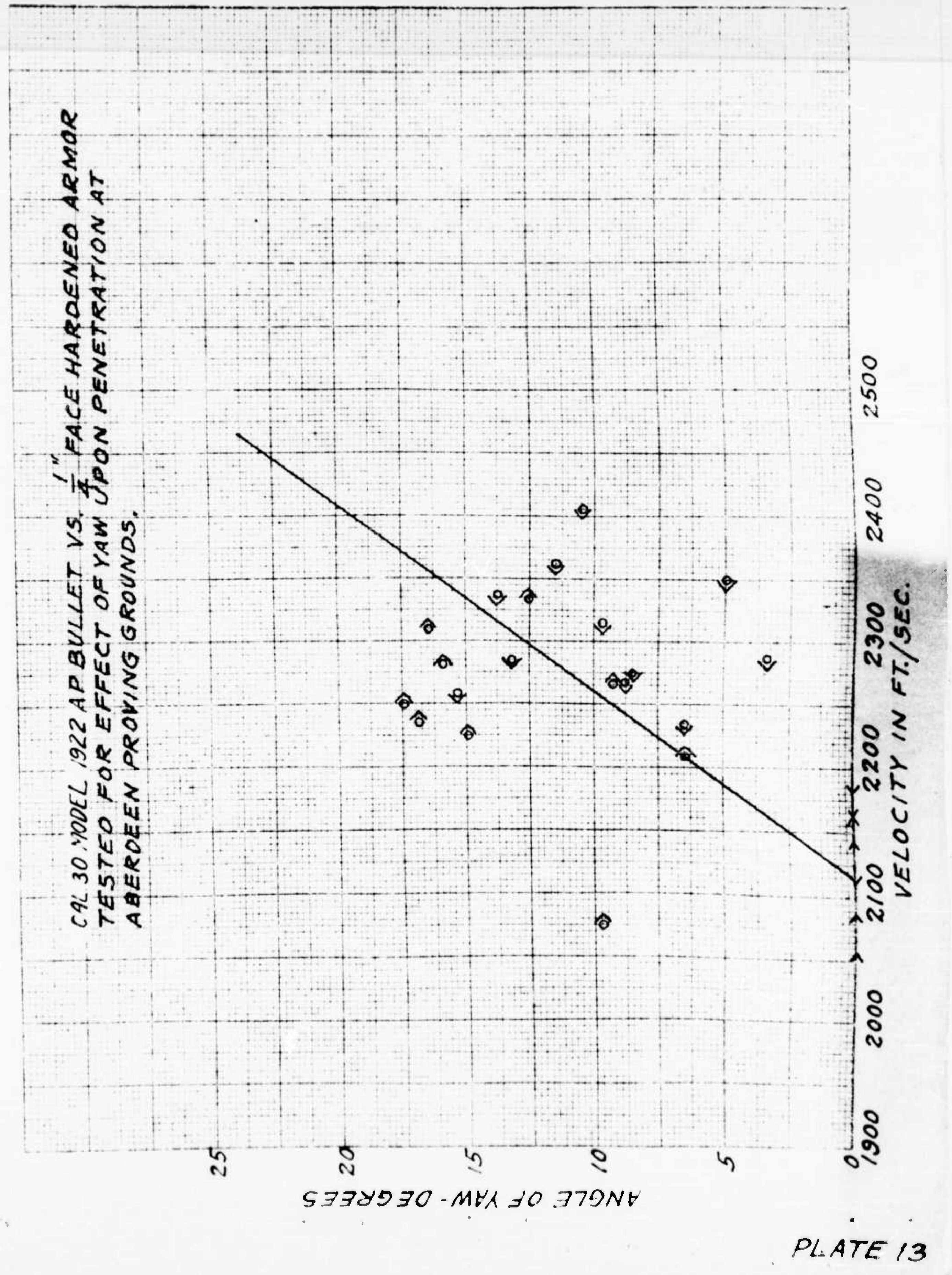
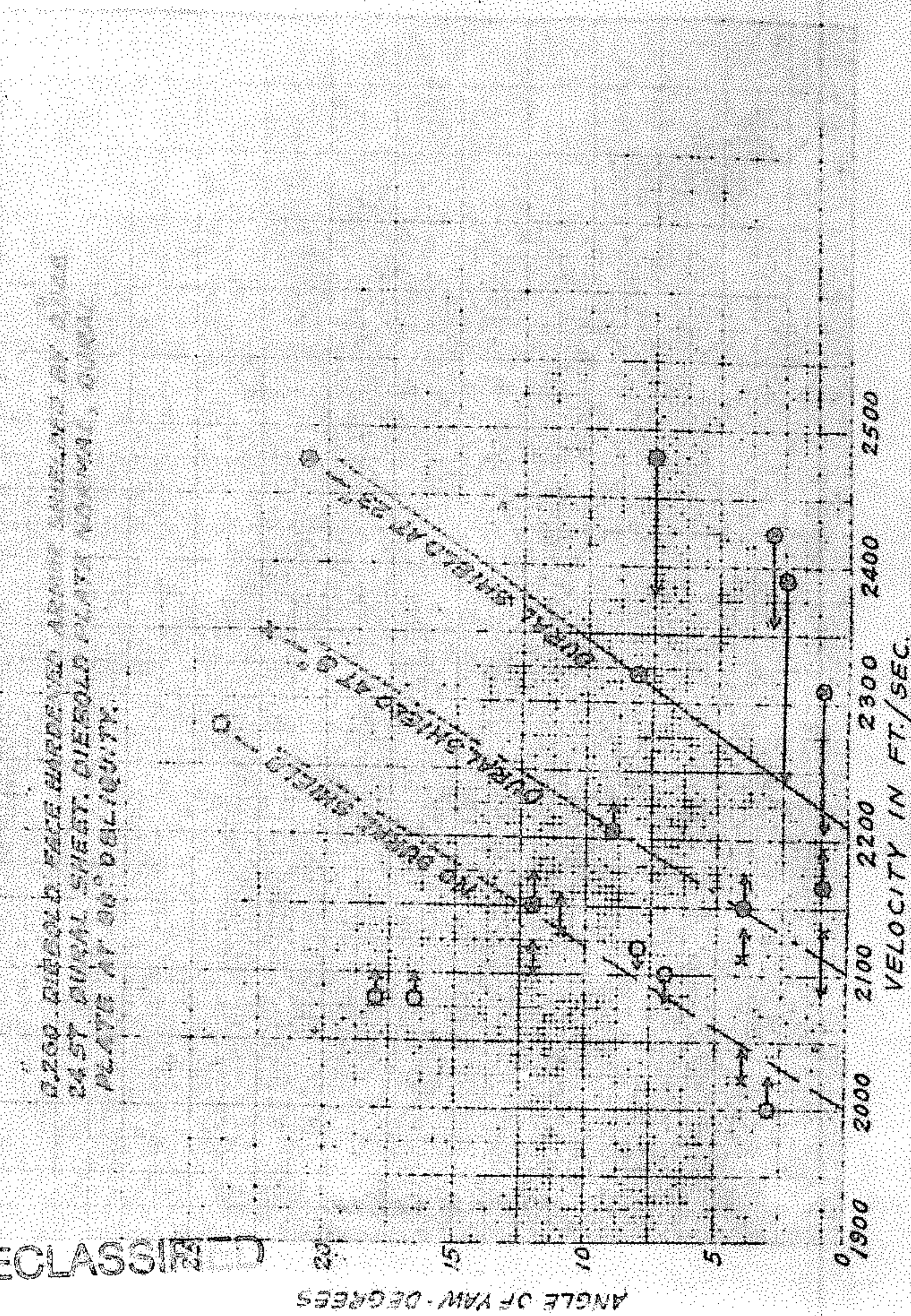

CAL 30 MODEL 1922 AP BULLET VS. 1/4" FACE HARDENED ARMOR
TESTED FOR EFFECT OF YAW UPON PENETRATION AT
ABERDEEN PROVING GROUNDS.
VELOCITY IN FT./SEC.
1900
2000
2100
2200
2300
2400
2500
ANGLE OF YAW - DEGREES
0
5
10
15
20
25

PLATE 13

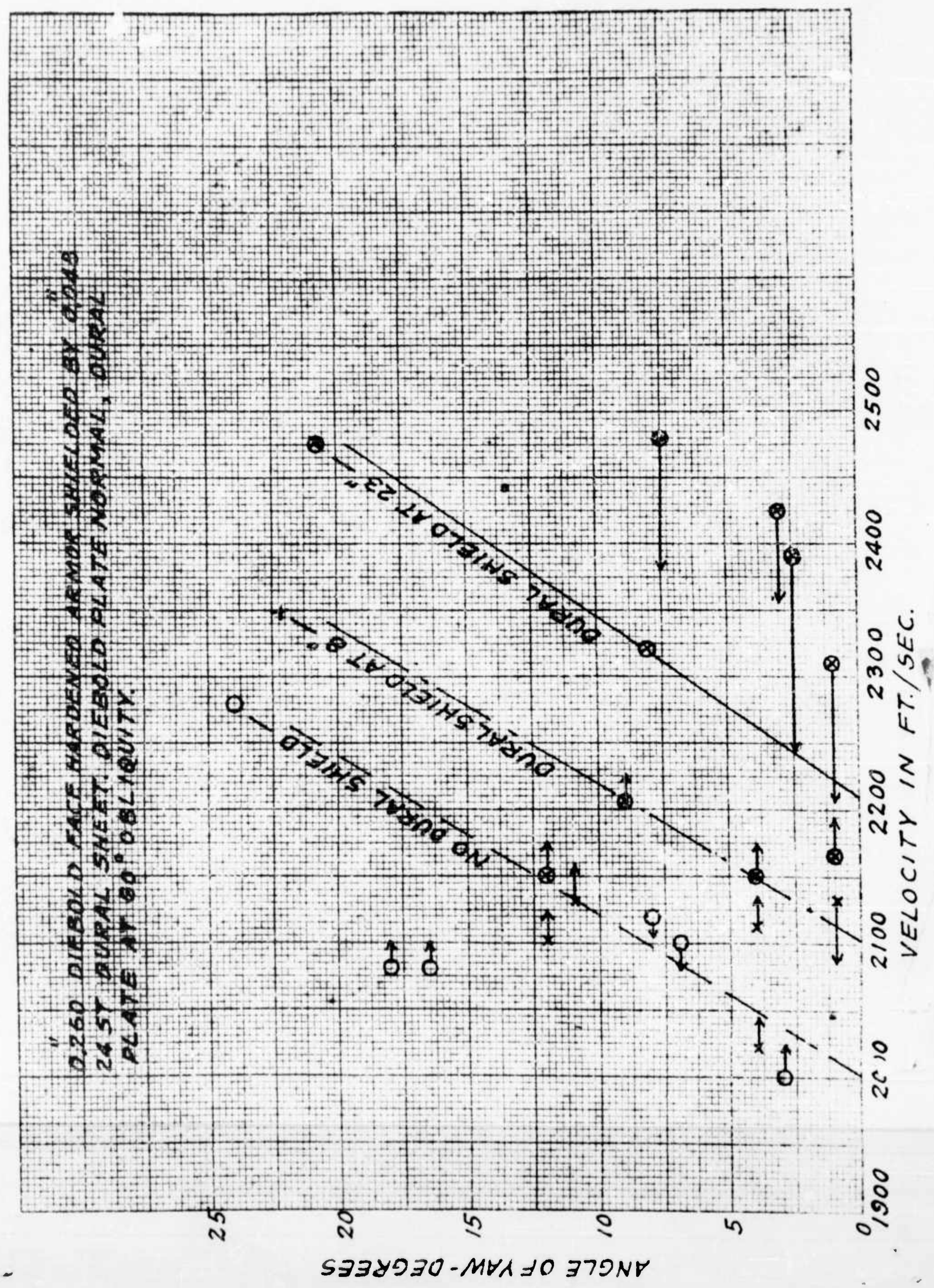


ANGLE OF YAW - DEGREES
0
5
10
15
20
VELOCITY IN FT./SEC.
1900
2000
2100
2200
2300
2400
2500
O — NO DURAL SHIELD
X — DURAL SHIELD AT 5"
● — DURAL SHIELD AT 23"

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.

DATE

IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE.



N. R. L. 31A

SUMMARY OF RESULTS WITH GRATINGS.

Item	Material	a	w	d	a^{1}/a	a^{11}	Obliquity of First Plate	Yaw (Average)		[illegible]	e_1	Limit Velocity	[illegible]
1.	17 ST Dural	0.65	0.20	0.20	0.80	0.185	30°	2°	1/8" Dural sheet clamped against back of grating.	30	[illegible]	1487	1.35
2.	17 ST Dural	0.50	-	0	1.00	0.18	30°	2°	1/8" Dural sheet clamped against back of plate.	30	[illegible]	1790	1.37
3.	17 ST Dural	0.50	0.125	0.25	0.60	0.106	30°	7°	.27" STS plate at normal 6" behind Dural.	0	0.392	2340	0.64
4.	17 ST Dural	0.204	-	0	1.00	[illegible]	30°	4°	.27" STS plate at normal 6" behind Dural.	0	0.354	2310	[illegible]
5.	17 ST Dural	0.50	0.094	0.281	[illegible]	[illegible]	30°	-	.27" STS plate at normal 6" behind Dural.	0	[illegible]	[illegible]	0.66
6.	17 ST Dural	0.50	0.11	0.39	0.45	[illegible]	30°	-	.253" STS plate at normal 6" behind Dural.	0	0.365	[illegible]	[illegible]
7.	17 ST Dural	0.50	0.18	0.39	0.67	[illegible]	30°	-	.253" STS plate at normal 6" behind Dural.	0	[illegible]	[illegible]	0.61
8.	17 ST Dural	0.25	0.094	0.406	[illegible]	[illegible]	30°	-	.253" STS plate at normal 6" behind Dural.	[illegible]	[illegible]	[illegible]	[illegible]
9.	STS	[illegible]	0.094	0.406	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] STS plate at 30°, [illegible] behind grating.	[illegible]	[illegible]	[illegible]	[illegible]
10.	STS	0.098	-	0	1.00	[illegible]	30°	[illegible]	.253" STS plate at 30°, [illegible] behind this plate.	[illegible]	[illegible]	[illegible]	[illegible]
11.	17 ST Dural	[illegible]	0.20	[illegible]	0.80	[illegible]	[illegible]	-	.26" STS plate at normal 6" behind grating.	[illegible]	[illegible]	[illegible]	[illegible]
12.	24 ST Dural	0.048	-	0	-	0.017	60°	3°	.26" face-hardened armor at normal 27" behind Dural.	0	[illegible]	[illegible]	[illegible]

[redacted]

Plate 15

JUN 30 1939

SUMMARY OF RESULTS WITH GRATINGS.

Item	Material	e	w	d	e^1/e	e^{11}	Obliquity of First Plate	Yaw (Average)		θ	e_1	Limit Velocity	K_e
1.	17 ST Dural	0.65	0.20	0.20	0.80	0.185	30°	2°	1/8" Dural sheet clamped against back of grating.	30	0.230	1480	1.35
2.	17 ST Dural	0.50	-	0	1.00	0.18	30°	2°	1/8" Dural sheet clamped against back of plate.	30	0.223	1700	1.00
3.	17 ST Dural	0.50	0.125	0.25	0.60	0.106	30°	7°	.27" STS plate at normal 6" behind Dural.	0	0.392	2350	0.69
4.	17 ST Dural	0.204	-	0	1.00	0.073	30°	5°	.27" STS plate at normal 6" behind Dural.	0	0.354	2310	0.57
5.	17 ST Dural	0.50	0.094	0.281	0.50	0.089	30°	-	.27" STS plate at normal 6" behind Dural.	0	0.373	2350	0.66
6.	17 ST Dural	0.50	0.11	0.39	0.45	0.080	30°	-	.253" STS plate at normal 6" behind Dural.	0	0.345	2400	0.59
7.	17 ST Dural	0.50	0.18	0.39	0.57	0.102	30°	-	.253" STS plate at normal 6" behind Dural.	0	0.371	2430	0.61
8.	17 ST Dural	0.25	0.094	0.406	0.40	0.042	30°	-	.253" STS plate at normal 6" behind Dural.	0	0.302	1950	0.76
9.	STS	.255	0.094	0.406	0.40	0.102	30°	7°	.253" STS plate at 30°, 1-3/4" behind grating.	30	0.355	2600	0.68
10.	STS	0.098	-	0	1.00	0.098	30°	7°	.253" STS plate at 30°, 1-3/4" behind thin plate.	30	0.351	2550	0.70
11.	17 ST Dural	0.203	0.20	0.20	0.80	0.058	30°	-	.26" STS plate at normal 6" behind grating.	0	0.327	2380	0.56
12.	24 ST Dural	0.048	-	0	-	0.017	60°	3°	.26" face-hardened armor at normal 23" behind Dural.	0	0.294	2210	0.59

Plate 15